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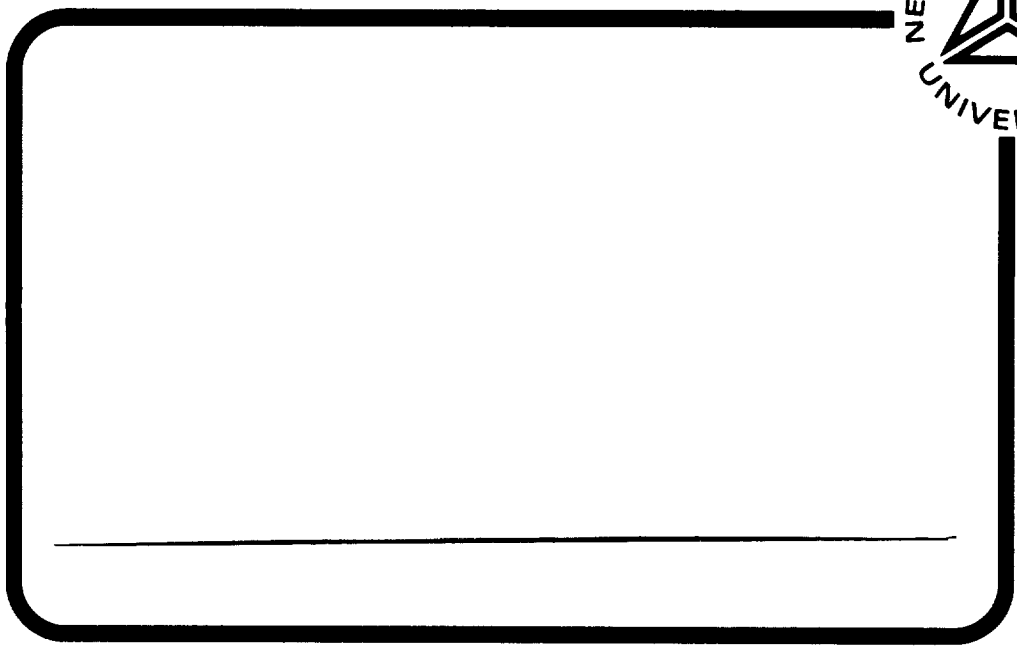

THE KLIPSCH SCHOOL OF

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RAIN RATE STATISTICS IN SOUTHERN NEW MEXICO

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Rain Rate Statistics

in

Southern New Mexico

Frank J. Paulic, Jr.

April 20, 1997

Technical Report

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Table of Acronyms

ACTS	Advanced Communication Technology Satellite
APT	ACTS Propagation Terminal
CRG	Capacitive Rain Gauge
DACS	Data Acquisition and Control System
IF	Intermediate Frequency
NASA	National Aeronautics and Space Administration
NMSU	New Mexico State University
RF	Radio Frequency
STel	Stanford Telecommunications, Inc.
STGT	Second Tracking Data Relay Satellite System Ground Terminal
TBRG	Tipping Bucket Rain Gauge
TDRSS	Tracking Data Relay Satellite System
UTA	University of Texas at Austin
VPI	Virginia Polytechnic Institute and State University

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1 Introduction

1.1 Reason for Experiment

Telecommunications research today is focusing on increasing the number of users in a given transmission medium. For microwave bands, this medium is saturated or has reached the limit where new technology is necessary to increase the number of channels in a given bandwidth that is assigned to a service provider[3]. Alternatively, the frequency spectrum in microwave telecommunication can be extended to higher frequency bands. These bands are designated, on an international basis, as the Ku, K, and Ka bands, which encompass the frequencies between 12.4 GHz and 32.0 GHz. Technology exists for practical telecommunications at these frequencies; unfortunately, for frequencies above 10 GHz, atmospheric conditions are the predominate causes of attenuation. We know much about the atmospheric characteristics at these high frequencies, such as the atmospheric absorption due to gases. The dominant atmospheric degradation on high frequencies above 10 GHz is rain, and fortunately, over a high percentage of the Earth's land mass, it rains only a small percentage of time. Therefore, research in determining the rain rate statistics for a given region is a valuable asset for establishing the required operating parameters for low link margins on satellite links.

Presently, an experiment funded by the National Aeronautics and Space Administration (NASA), called the Advanced Communication Technology Satellite (ACTS) Propagation Experiment, is collecting data in which link designers can determine if satellite communication in the Ka band is practical. Seven locations on the North American continent, known as ACTS Propagation Terminal (APT) sites, are monitoring these two frequencies from the ACTS satellite located at 100°W longitude in a geostationary orbit. The table[4] below lists the APT sites with their coordinates, designated climate (rain rate) regions, and the antenna's elevation angle.

Table 1 ACTS Sites

ACTS Site	CCIR/Global Climate Zone	Latitude	Longitude	Elevation Angle
Vancouver, BC	D / B1	49.26°N	123.25°W	29.26°
Ft. Collins, CO	E / B2	40.40°N	104.70°W	43.02°
Fairbanks, AK	C / A	64.86°N	147.82°W	7.96°
Clarksburg, MD	K / D2	39°N	77°W	38.91°
White Sands, NM	M / F	32°N	107°W	51.98°
Norman, OK	M / D1	35°N	97°W	49.22°
Tampa, FL	N / E	28°N	82°W	52°

New Mexico State University's (NMSU) Electrical Engineering Department has obtained a grant from NASA, as a partner with Stanford Telecommunications, Inc. (STel), to maintain an APT site in Southern New Mexico. This site is located on the grounds of the Second Tracking and Data Relay Satellite System (TDRSS) Ground Terminal (STGT), part of Goddard Space Flight Center's White Sands complex near Las Cruces, New Mexico. The data collected at the APT are local meteorological data and two beacon signals from ACTS, along with radiometer measurements of the atmosphere that correspond to the two beacon frequencies. The 20 GHz beacon has spacecraft telemetry modulating the beacon carrier, while the 27 GHz beacon is a pure tone. Users of the APTs are responsible for site maintenance, such as equipment calibrations. They also perform preprocessing of the data, removing abnormalities in the beacon and radiometer signals, such as losses due to equipment malfunctions and also removing satellite's diurnal motion. The preprocessing of the data collected at White Sands APT is performed by ACTSEdit, a software program discussed later in this report. The raw and processed data from the New Mexico APT is forwarded to STel for further processing.

1.2 Goals for Report

This report will focus on empirical rain-rate distributions derived from the software developed at NMSU for extracting rain rate estimates from data collected at the New Mexico ATP site. This software enables one to visually inspect the effects rain rate has on the attenuation of the two ACTS beacon signals, and the derived rain rate will be used to determine the region's rain rate rain-rate distribution. This distribution will be compared to the Global prediction model. Empirical rain-rate distributions will then enable satellite system designers to determine the appropriate minimum link margin or the need for site diversity for a required link availability.

2 Experimental Hardware / Software

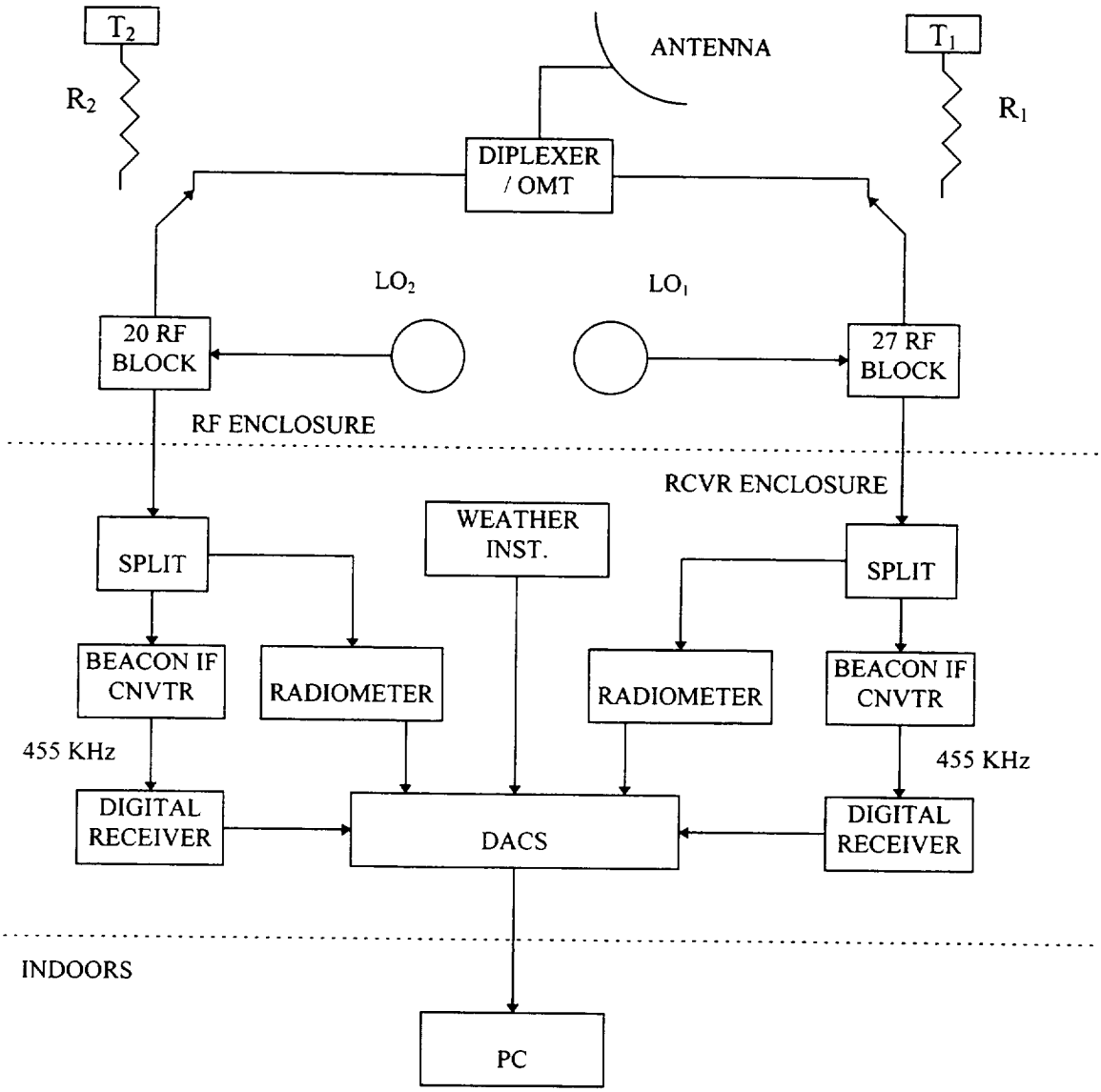
The receiver and data acquisition system was developed by Virginia Polytechnic Institute and State University (VPI). Development include integrating the hardware and the design of the Data Acquisition and Control System (DACS). Hardware includes the beacon and radiometer receivers and the parabolic antenna which was acquired as government furnished equipment. Software support was also developed at VPI; ACTSview and ACTSEdit, which is discussed in Section 3. The following figure is a block diagram of the APT. For a detailed description, refer to the APT manual[4].

2.1 Beacon Receiver

The ATP at STGT is located at 106° 36′ 48″ west longitude, 32° 32′ 40″ north latitude, at an elevation of 4,787 feet (1.459 km) above sea level. A diagram of the receiver hardware is shown in Figure 1. The antenna is a 1.2 meter parabolic dish, receiving 20.185 GHz and 27.435 GHz beacons from the ACTS geostationary satellite located at 110° azimuth, with an elevation angle of 51°.

FIGURE 1

ACTS PROPAGATION TERMINAL



The beacon receiver monitors the signal strength of the 20 GHz and 27 GHz beacon signals. From the data collected, one can determine link availability statistics for an earth station located in the surrounding STGT climate region. Signal attenuation at these frequencies is predominately caused by rain and condensation in clouds. Attenuation caused by these two events are known as rain fade and cloud fade. The attenuation statistic is a function of rain rate statistic, and these two statistics should correlate to one another. We also know that oxygen and water vapor in the atmosphere attenuates the signal. For example, referring to Table 1, Fairbanks, Alaska has the lowest elevation angle; thus, its has the longest propagation path in the atmosphere. Also, Fairbanks is located the furthest from the satellite's antenna bore sight. As expected, Fairbanks has the lowest link margin of all the APT sites, due to the gaseous absorption and the received signal power.

The Radio Frequency (RF) enclosure, as indicated in Figure 1, is mounted behind the antenna's feed horn. It contains a diplexer which separates the two vertical polarized beacon signals, each to a heterodyne receiver whose Intermediate Frequency (IF) output is fed into the receiver enclosure. The IF input to the receiver enclosure is split in two directions. One is to a radiometer which measures the sky noise and the other to a mixer which downconverts the beacon signal. The signal processor in the receiver enclosure digitizes the radiometer and beacon level outputs for storage in a personal computer located nearby.

2.2 Radiometer Receiver

The purpose of this experiment is to measure attenuation due to changes in the atmosphere, using both a constant power beacon from the satellite and a ground base radiometer. In reality, the radiated power in the beacon varies due to satellite motion, on-board power supply variations, changes in transmitter power, or antenna gain variation caused by thermal variation resulting from the changing angle of the sun's energy [1]. With only beacon measurements, atmospheric attenuation estimates would be

contaminated by radiated power variation, and these estimates would be valid for attenuation measurement greater than a few decibels. For low link margin systems, these measurements are inadequate, unless the radiated power variation is canceled. The beacon and radiometer combination can increase the measurement accuracy to within half a decibel. The radiometer measures signal attenuation caused by absorption due to atmospheric gases (oxygen and water vapor) and clouds. The radiometer's output is a voltage, which corresponds to the sky brightness temperature, T_{SKY}. The relationship between T_{SKY} and the atmospheric absorption is demonstrated by the following equation[6]:

$$ARD = 10 \cdot \log \frac{T_M - T_C}{T_M - T_{SKY}}$$

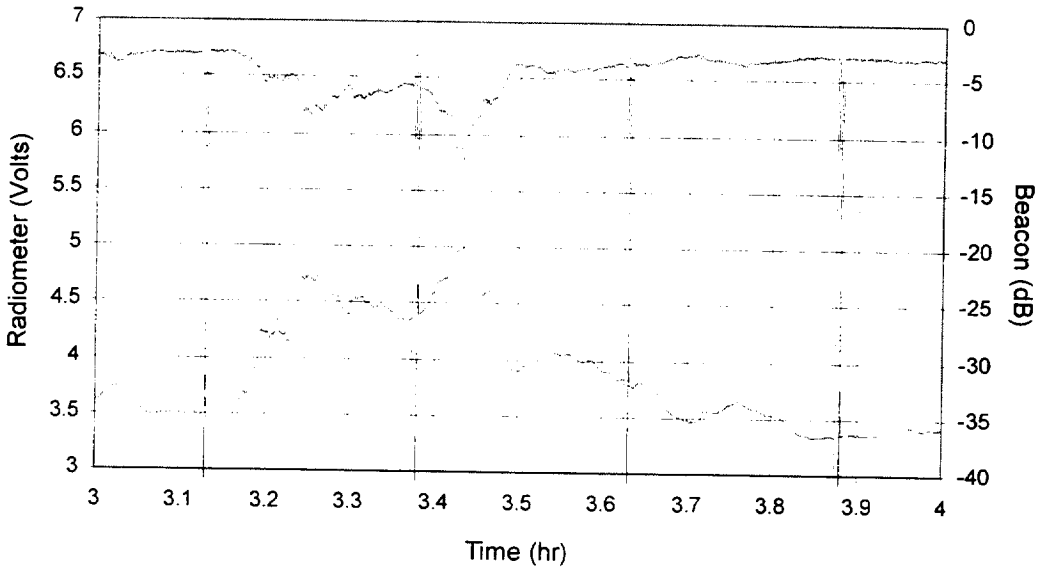
where

ARD is the Radiometric Derived Attenuation,

T_C is the cosmic back ground temperature (2.75°K), and

T_M is the medium temperature (approximately 290°K).

The radiometer measures the sky temperature (energy spectrum) in a 50 MHz bandwidth centered on the two beacon signals, which can correlate a rise of spectral energy caused by atmospheric absorption and the attenuation of the beacon signals. Thus the beacon and radiometer combination can extract the radiated power variation, and beacon attenuation due to atmospheric absorption can be accurately measured. Figure 2 shows the correlation between atmospheric absorption and beacon attenuation. The upper curve is the beacon signal whose clear-air baseline is approximately -4 dB, while the lower curve is for the radiometer whose baseline level is 3.4 volts (also note the 15 minute interval calibration shown below, which appears as two parallel vertical lines). The baseline of the radiometer is the clear-air gaseous absorption, which has a low amplitude sinusoidal variation (one cycle per day) due to the satellite's diurnal motion.



Cloud fade event on August 8, 1995. Top trace is 20 GHz beacon signal. Bottom trace is the radiometer. Note the 15 minute calibration artifacts on the radiometer signal.

Figure 2 Correlation Between 20 Beacon and 20 Radiometer.

Rain scatters and absorbs the beacon signal; a higher rain rate translates to an increased signal attenuation. Unfortunately, the relationship between signal attenuation and radiometer output is limited to approximately 8 dB of signal attenuation. Rain gauges are needed to correlate rain rate and signal attenuation beyond radiometer measurements at the site's location. Further statistics are needed to account for rain events along the path length. Low elevation angles, which translate to longer path lengths, tend to have an increased likelihood that the signal would encounter a rain cell when a rain event occurs. Thus, the APT at Fairbanks, whose elevation angle is 8°, would be more likely to encounter more rain cells than the other APTs along the signal's propagation path. These statistics are embedded in the attenuation prediction model, which is a function of the climate region's rain rate and the sites' elevation angle.

Radiometer output is derived from measuring the noise power (square-law detector) within the receiver's IF bandwidth of 50 MHz, which was split by a power splitter in the

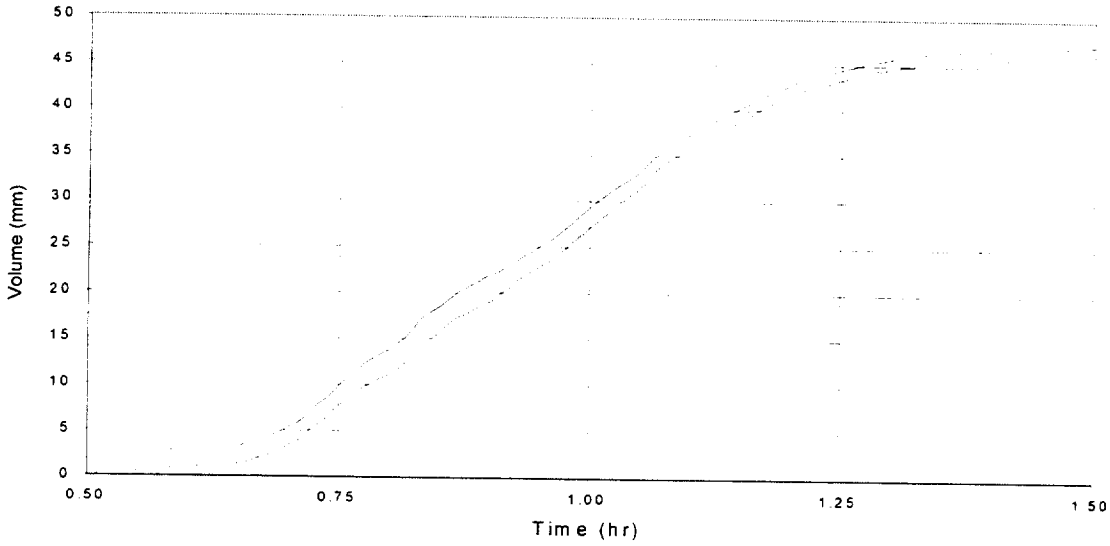
IF subassembly. The IF contains both radiometer and beacon signals. Two types of calibrations are necessary to quantify radiometer output and preserve its accuracy: absolute calibration and automatic calibration. Absolute calibration removes baseline drift errors caused by changes in system noise temperature. This is accomplished by terminating the receiver's input (antenna's feed horn) with two loads at significantly different physical temperatures, a hot load (ambient temperature) and a cold load (liquid nitrogen whose boiling point temperature is 77°K). This procedure is described in the APT Manual and is performed approximately every two weeks. Automatic calibration removes errors due to changes in gain, by periodically (every 15 minutes) switching the RF input alternatively to a reference load and a noise diode. The reference load and the noise diode provide a known increment of noise to the receiver input, thus the gain changes can be determined.

2.3 Rain Gauge

Two types of rain gauges are used at the APT site, an analog version and a mechanical version. The analog version is a capacitive rain gauge (CRG), manufactured by R.M. Young, with its output voltage proportional to rain accumulation. Capacity for this rain gauge is 500 ml, which corresponds to 50 mm of rain. The mechanical version is a tipping bucket rain gauge (TBRG). Tipping occurs for every 0.254 mm of rain accumulated, which generates a pulse that is recorded. Unlike the capacitive rain gauge, there are no electronics to record accumulation; therefore, output readings are not affected by temperature drift. The tipping bucket also does not require purging (resetting the rain accumulation to zero) after a rain event. The disadvantage to the tipping bucket is the non-uniform sampling due to tips.

The monsoon season occurs during the summer months in Southern New Mexico, where the rain rate can exceed 120 mm/hr for a short duration. The fast response time of the capacitive rain gauge and the sampling rate of six seconds enables accurate measurement

of high rain rates; therefore, our rain rate statistics can be accurately derived from data collected from this gauge. Although it has been shown that the TBRG can accurately record high rain during New Mexico's monsoon season, the uniform sampling of the CRG makes processing of the data easier. The figure below shows the response of the two gauges to a high rain rate event, with both having an accuracy of ±1ml.



Measured rain accumulation on August 17, 1995. Top trace represents capacitive rain gauge output (CRG), bottom trace represents the tipping bucket rain gauge (TBRG).

Figure 3 CRG vs. TBRG Accumulation

Since the electronics within this gauge are subject to temperature change, which results in output voltage drift, a biweekly calibration is required. The procedure for calibrating the CRG is as follows:

- Purge the capacitive rain gauge (>500ml) and in ACTSview (see Section 3.1), record the CRG output (empty) reading.

- Input 50ml of water (**measurand**) and record the output in millimeters of water (**real unit** - not calibrated) reading.

- Record the measured accumulation in millimeters for each 50 ml input until 500 ml have been added (a volume of 500 ml corresponds to 50 mm of rain accumulation). The CRG should self-purge when 550 ml of water is accumulated. If it does not, the CRG is most likely obstructed by insects or frozen water.

- Input the measurement into Crg_cal.xls (see Section 3.4.4). This measurement is referred to as the **calibration data**.

This calibration is incorporated into the software which extracts rain rate from the accumulative measured rain. After each rain event it is also imperative to purge the rain gauge, since multiple rain events will fill the capacitive rain reservoir and it will self-purge. This self-purging during a rain event will interrupt the monoticity of rain accumulation, and extracting the rain rate from this interruption will be difficult to analyze.

2.4 Data Acquisition and Command System

The Data Acquisition and Command System (DACS) is used to collect and control the data collection process[4]. The DACS controls the sampling of the beacon signal, radiometer power measurements, and rain accumulation measurements from the rain gauges. It also provides controls for automatic calibration of the radiometers (see Section 2.2). The sampling period is one second for the beacon and radiometer data, and six seconds for the capacitive rain gauge. The TBRG is asynchronous: the sample is time stamped whenever a tip occur, and is shared among other meteorological data. Each second is also recorded, referenced from the APT computer, which is synchronized periodically with an external reference signal, Universal Time from Fort Collins, CO, via

a 10 MHz active dipole antenna. The sampled data are collected and packetized for storage on a personal computer located at the APT site. This data is downloaded weekly on floppy disks for further processing at the NMSU Electrical Engineering Department.

3 Software Support

3.1 Overview of ACTSView

ACTSView is a program to enable an operator to view the DACS real-time data collection process, which includes the beacons attenuation level, radiometers output voltage level, meteorological data, and the system's environmental parameters (voltage levels, internal equipment temperatures, etc.). A listing of environmental parameters is available in the APT handbook[4]. This program also has the capability of viewing past raw data files.

3.2 Overview of ACTSEdit

We use ACTSEdit to preprocess the raw beacon and radiometer data. This preprocessing includes removal of data anomalies, applying calibration to radiometer measurements, and removing beacon signal variation, due to satellite variability as discussed in Section 2.2. The raw data files collected at the APTs are designated with an ".rv0" extension, where the preprocessed data has a ".pv0" extension. The rv0 and pv0 data files are forwarded to the ACTS data archive at University of Texas at Austin (UTA). We are the only site which preprocesses the rv0 data with ACTSEdit to produce the pv0 files. Other APT sites preprocess their rv0 data with Robert Crane's [5] preprocessing technique and these files are designated as pv2 files. The difference between the two preprocessing technique is that Crane's preprocessor uses a different calibration procedure, which removes anomalies statistically. Our conjecture is that the caretakers of each site are familiar with the everyday events pertaining to the APTs, such as rain events and

equipment malfunctions. Thus it is reasonable for the caretakers to remove abnormalities, such as equipment glitches and calibrations which affect beacon signal and radiometer levels. (References are available explaining the procedures for useing ACTSEdit [4][3].) We also forward our rv0 and pv0 files to STel, where they preprocess our rv0 file with Crane's preprocessor for a comparison evaluation with our pv0 file, and this pv2 file is also forwarded to UTA.

3.3 File Generating Program

A Visual Basic 3.0® program (decomp5.exe) has been developed to extract (demultiplex) the desired data from a rv0 data file. The data, which can be extracted and which pertains to this report, are the time, beacon signals, radiometer readings, and rain accumulation from the two rain gauges.

Files generated from this program are data files for the EXCEL® spreadsheet, including rain.xls, rainrate.xls. These programs are described in the next section. The user designates the name of the data file with the following format: "pyymmddx.txt". The prefix "p" designates which program the data file supports. The date "yymmdd" (year-month-day) is the same date as that on the rv0 data file. The suffix "x" represents the ascending order of the alphabet and is only needed if there is more than one support file for a given day. All data files will have ".dat" as the extension.

Each data file has a header (control parameters) for a particular program. The first entry is the date (yymmdd), with an extension if needed. The second entry is the time span of the data file. The third entry will have the rain accumulation for the CRG from the previous rain event if the CRG was not purged. The last entry will have the carryover for the TBRG accumulation. The first entry is the only one necessary for all programs. The following table will summarize the format of a data file designated for a particular program.

Table 2 Data File Format

EXCEL® Program	Prefix	Time Span	CRG Accumulation	TBRG Accumulation
rain.xls	r	1 or 2 half hour(s)	(entry if needed)	(entry if needed)
rainrate.xls	t	1,2,3, or 4 hour(s)	(no entry)	(no entry)

Each EXCEL® spreadsheet requires a particular set of data. The following table summarizes the data extracted from the rv0 data file.

Table 3 Data Extraction

EXCEL® Program	20 GHz Beacon	27 GHz Beacon	20 GHz Radiometer	27 GHz Radiometer	CRG	TBRG
rain.xls	x	x	x	x	x	x
rainrate.xls			x	x	x	

The procedure for developing a data file for Rain.xls is as follows:

- Initiate the file generating program (c:\vb\aptdelog\ decomp5.exe).
- Input the rv0 file name, (yymmddnm.rv0) with the associated path.
- Select the following; Beacon 20, Beacon 27, Radiometer 20, Radiometer 27, CRG, and TBRG. Click on the "DONE" button.
- Input the start and end time (hhmm), spanning a half-hour or one hour. This program does not function if the user terminate the time at the 24 hour mark. One must end the time a few minutes (2358) before the 24 hour mark.

- Enter the output file name with the following notation, "c:ryymmdd.dat", where yymmdd indicates the date. Suffix the date with the ascending order of the alphabet, if more than one time span is needed on this date.

- Move the file(s) generated from this program, listed in the same directory as the program's executable file, to the data directory under the rain directory. See the paths for this report in the Appendix.

- Open EXCEL® spreadsheet, and access the file that was generated, with a ".dat" extension. Insert a row at the beginning of the file. In the first column of the inserted row, write the file's date, yymmdd, followed by an appropriate alphabet if needed. In the second column, write the time span, "1" for a half hour, or "2" for an hour. Remove any text at the end of the file.

- If necessary, add rain accumulation for the CRG and TBRG in the first row from the previous rain event if the CRG was not purged (or continuation of the same rain event).

- Save the file with a ".txt" extension. The txt extension will let the user know that the dat file has been modified. Also the txt extension formats the file with 15% reduced capacity.

- Close the worksheet, answer **NO** to the pop up window prompt.

- When all the files have been converted to the ".txt" extension, delete the ".dat" extension files.

Use the same procedure prescribed above for generating data files for the Rainrate.xls program. The differences are the files' prefixes, the data extracted, and the time span.

3.4 Excel Programs / Files

Programs were developed to view the correlation between beacon signal and rain rate events. Programs for evaluating rain statistics were also developed. Support files (data and CRG calibration data) for these programs were needed to reduce the redundancy of these programs. The path for all the programs and files in this section are listed in Appendix 5.

3.4.1 Rain.xls

Rain.xls is an EXCEL®spreadsheet program that enables one to view the correlation between beacon signal attenuation and rain rate. Four graphs are generated; rain rate (mm/hr), 20 GHz beacon signal attenuation vs. rain rate, 27 GHz beacon signal attenuation vs. rain rate, and capacitive rain gauge accumulation vs. TBRG accumulation. The time axis can span one half hour or one hour.

The support files that are associated with this program are the data files and the capacitive rain gauge calibration data. These files are accessed with a macro button designated as "Get File". This program has one worksheet, subdivided into three sections. The first section provides an evaluation of the slope and intercept of a linear regression line that would least square fit the capacitive rain gauge calibration data. The slope and intercept are used to estimate the CRG measurand. The second section is the imported data file designated for this program. The third section processes the imported data for generating rain rate and rain accumulation graphs. An example spreadsheet for this program is shown below without the macro button.

data date >	960715c															
Cal Date	960703															
input		reading	fit													
0	0.06	0.06	0.88867	960715	Rain Rate											
5	3.46	3.46	4.00067	960715	Rain Rate vs 20 Beacon											
10	9.21	9.21	9.2636	960715	Rain Rate vs 27 Beacon											
15	15.47	15.47	14.9933	960715	CRG vs TBRG Accumulation											
20	21.36	21.36	20.3844													
25	26.91	26.91	25.4643	initial CRG fil (A23)	30.3062											
30	32.18	32.18	30.2879	initial accumulate TBRG (A24)	23.876											
35	37.5	37.5	35.1573	final CRG fill	32.1002											
40	42.77	42.77	39.9809	final accumulateTBRG	25.654											
45	48.07	48.07	44.8319	number of half hours	2											
50	53.44	53.44	49.747													
				Limit for d/dt CRG Cal	3594											
SLOPE		1.09255														
INTERCEPT		-0.91091														
enter data below in cell A24				Note: Row 23 is set aside for initial conditions (.txt file)												
time (sec)	beacon 20	beacon 27	rad 20	rad 27	CRG	TBRG#1	TBRG#2	time (hr)	CRG Cal	CRG Cal Fill	d/dt CRG Cal	d/dt CRG Cal Fill	TBRG#1 *0.254	TBRG#2 *0.254	Accum-ulate TBRG	
960715c	2	30.3062	23.876													
54900	-3.17	-4.53	2.881	3.236				15.25	30.3062	30.3062		0	0	0	23.876	
54901	-3.21	-4.63	2.881	3.237				15.2503		30.3062		0	0	0	23.876	
54902	-3.03	-4.46	2.884	3.235	32.22			15.2506	30.3245	30.3245		0	0	0	23.876	

Figure 4 Rain.xls Spreadsheet

The calibration data (see Section 3.4.4) is used to transform the CRG readings to actual rain accumulation. This transformation in rain.xls proceeds as follows:

- The date of the data file (ryymmdd.txt) loaded into Rain.xls will retrieve the preceding date calibration data from crg_cal.xls.

- Rain.xls will estimate the slope of the **linear regression line** (least squares) on the calibration data, which will be used to estimate the measurand (see Section 2.3). The following linear equation shows the relationship between the measurand and the real units:

$$\text{real units} = \textbf{intercept} + \textbf{slope} * \text{(measurand)}$$

EXCEL's® SLOPE function determines the slope of the linear regression line with the following equation:

$$\text{slope} = \frac{n\sum_i x_i y_i - \left(\sum_i x_i\right)\left(\sum_i y_i\right)}{n\sum_i x_i^2 - \left(\sum_i x_i\right)^2}, \quad i = \{1,2,..,n\}$$

where n is the number of data points (measurements), x_i is the independent data points (measurand), and y_i is the dependent data points (real units).

- Rain.xls will estimate the intercept of the linear regression line on the calibration data, which will be used to estimate the measurand offset. The equation for the intercept of the regression line is:

$$\text{intercept} = \bar{y} - \text{slope} * \bar{x}$$

where $\bar{y}$ is the average value of the dependent data points (real units), and $\bar{x}$ is the average value of independent data points (measurand).

- The slope and intercept are used to estimate the measurand in CRG Cal discussed below

The data files, whose contents originated from an rv0 file, contain eight columns, designated from the first column as:

- time (sec) is the time in seconds relative to Universal Time.

- beacon 20 is the attenuation level for the 20 GHz beacon, sampled every second.

- beacon 27 is the attenuation level for the 27 GHz beacon, sampled every second.

- rad 20 is the noise power measurement for the 20 GHz radiometer, sampled every second.

- rad 27 is the noise power measurement for the 27 GHz radiometer, sampled every second.

- CRG represents the rain accumulation from the capacitive rain gauge, sampled every six seconds. The numeric numbers in this columns are the real units described in the calibration procedure above.

- TBRG #1 is asynchronous data from the TBRG whenever the tipping bucket accumulated 0.254 mm of rain. The numerical value of this event represents time lapse in hundredths of a second in which a tip occurred from the previous recorded second. This numerical value is not used in this program.

- TBRG #2 is an unexplained extension for TBRG #1.

Eight columns of the program's spreadsheet were developed to support the four graphs and to extract the rain rate from the calibrated rain data. The explanation for the designated columns is as follows:

- time (hr) converts the data file time from seconds to hours (decimal fraction) which will facilitate time readings on the graphs and is used as a parameter for evaluating rain rate (d/dt CRG Cal).

- CRG Cal calibrates the CRG rain accumulation data. The slope and intercept derived in the calibration process described above estimates the measurand from the real units

in the CRG column. The equation which transforms the real units to the estimated measurand is:

$$x_i = \frac{y_i - \text{intercept}}{\text{slope}}$$

where y_i is the value of the dependent data points (real units), and x_i is the estimated value of independent data points (measurand).

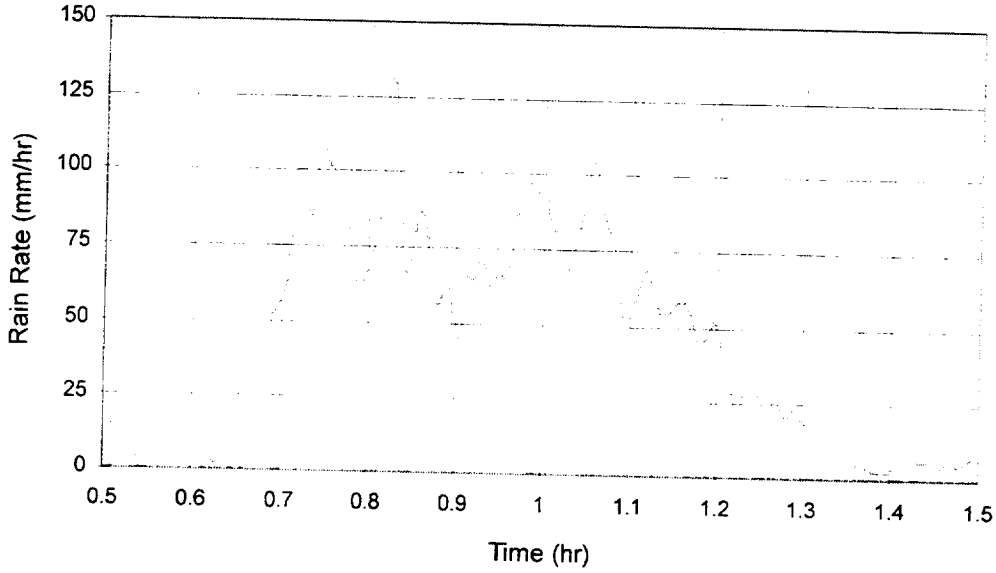
- CRG Cal Fill is a copy function that fills in empty CRG Cal rows, since CRG rain sampling is every six seconds. This column is used for the capacitive rain gauge accumulation vs. TBRG accumulation graph, without the need for interpolating between data points.

d/dt CRG Cal determines the slope for each of CRG Cal data points. This procedure uses EXCEL®'s SLOPE function to perform a running average on eleven data points symmetrically distributed about the data point whose slope is to be evaluated. This procedure approximates the rain rate (mm/hr) at each of the data points, and also inherently filters out sampling quantization errors, thus generating a noise free rain rate curve on the appropriate graphs.

$$\left.\frac{d(CRG)}{dt}\right|_{i=o} \approx \frac{n\sum_i x_i y_i - \left(\sum_i x_i\right)\left(\sum_i y_i\right)}{n\sum_i x_i^2 - \left(\sum_i x_i\right)^2}, \quad i = \{-5,-4,-3,-2,-1,0,1,2,3,4,5\}, \; n = 11$$

where the units for $\frac{d(CRG)}{dt}$ is mm/hr, n is the number of data points (measurements), x_i is the independent data points (six second intervals in a fraction of an hour), and y_i is the dependent calibrated data points (CRG Cal).

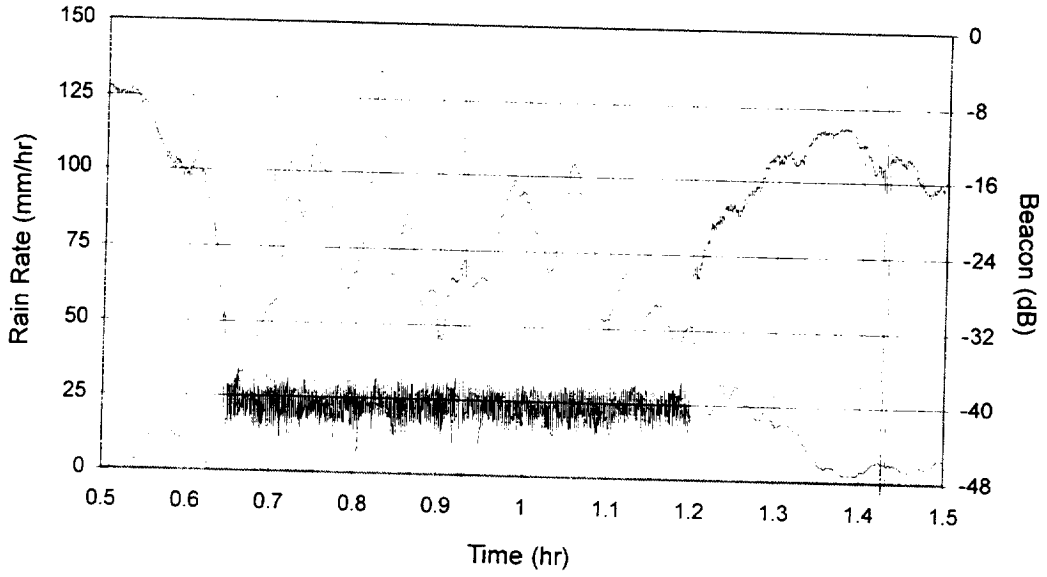
d/dt CRG Cal Fill has the same function as the CRG Cal Fill, when used on graphs pertaining to rain rate. The following figure demonstrates the calculated rain rate spanning a given rain event (time in decimal fraction).



Rain rate event on August 17, 1995

Figure 5 Rain Rate

The following graph shows the association between rain rate to the beacon's signal attenuation.



Rain rate event on August 17, 1995. Association between 27 GHz beacon signal and rain rate event (see Figure 5). Note the 15 minute interval calibration artifacts on radiometer signal.

Figure 6 Rain Rate vs. 27 GHz Beacon

A similar graph is generated for the rain rate comparison with the 20 GHz beacon.

- TBRG #1 0.254 marks the event when tips occurred with 0.254, relative to the data column designated as TBRG #1.

- TBRG #2 0.254 marks the event when tips occurred with 0.254, relative to the data column designated as TBRG #2.

- Accumulate TBRG accumulates the marked rain events in the TBRG #1 0.254 and TBRG #2 0.254 columns. It may be evident that a double tip has occurred, usually at high rain rates. If so, one of the double tips in the data file located in either of the TBRG #1 or TBRG #2 column should be removed.

3.4.2 Rainrate.xls

Rainrate.xls is an EXCEL® spreadsheet program that is similar to rain.xls program without the graphs. The support files which associate with this program are the data file and the capacitive rain gauge calibration data. The data file for this program only contains the time and the CRG data. The prefix for this file is "t", followed by the same format as that of the data file in the rain.xls program. The control parameters are also the same, with the exception that the time span of the rain event are integers that represent hours. Up to four hours can be processed with this program.

The purpose of this program is to evaluate the time span in minutes, for a set of rain rate values (point rain rate, **R** in mm/hr), in which the rain rate exceeds these values. The result of this tabulation is shown in the worksheet named "Results" shown below:

Table 4 Rainrate.xls Tabulated Results

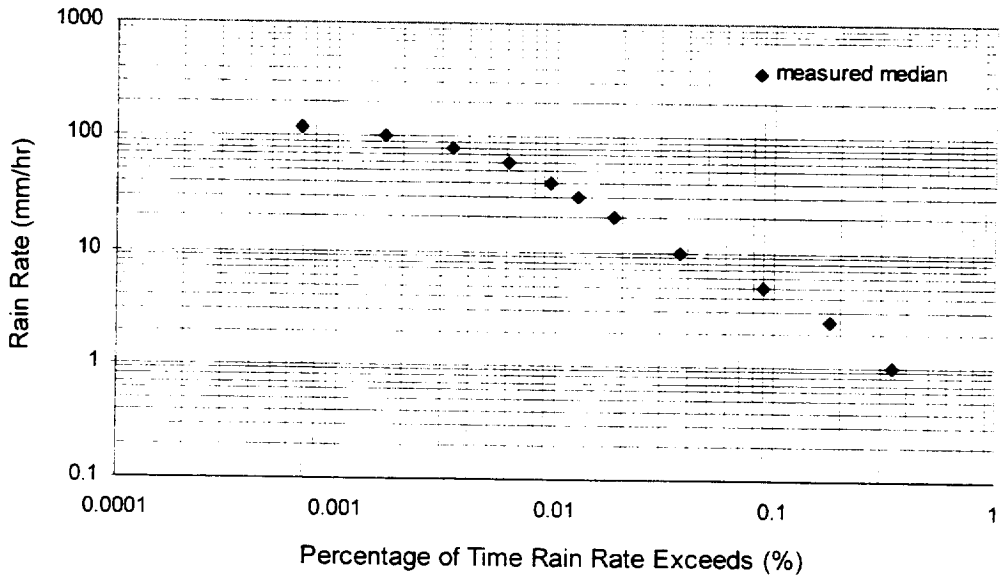
Date	950817													
Cal Date	950811													
Time (hr)	0.5	=>	2.5											
Total Accumulation (mm)	46.833													
Expected Number of CRG Samples	1200													
Number of CRG Samples	1200													
Rain Rate (mm/hr)	120	100	80	60	40	30	20	10	5	2.5	1			
Time (min) >= Rain Rate	0.6	3.5	11.9	22.6	32.1	34.6	38.9	45.8	56.6	67.3	81			
Formatted for RAINSTAT XLS file														
950817	0.5	2.5	0.6	3.5	11.9	22.6	32.1	34.6	38.9	45.8	56.6	67.3	81	46.833

For each rain event, the exceedance time for each rain rate value in the "result" worksheet is copied to another EXCEL® spreadsheet program (rainstat.xls), which is used for evaluating the yearly cumulative distribution of rain rates.

3.4.3 Rainstat.xls

Rainstat.xls is an EXCEL® spreadsheet program, which encompasses all rain rate events for the years 1995 and 1996. The year for this program begins in October, the emergence of the winter's low rain rate season, followed by the dry season. The year terminates at the end of the summer's monsoon season, which continues through the month of September. The monsoon season defines the specified year. Although ACTS' data year begins on December 1, the available rain rate data used in this analysis encompassed only a few years, thus hindering starting the season in December (so as not to start in the middle of a season). After a decade of collected data, one can arbitrarily change the year's start date to any chosen time of the year.

This program derives the average percentage of time in a year that the rain rate value is exceeded. The time exceeded for each rain rate value for all the recorded rain events for the years of 1995 and 1996 (defined above) are totaled. The totals are divided by the number of days spanning the two years and then converted to percentages. Below is a plot a the measured point rain rate versus percentage of yearly (average) exceedance.



Measured median rain rate distribution (2 year average - 1995,96)

Figure 7 Rain Rate Distribution

This "measured" exceedance time is compared to the Global prediction model, whose distribution is lognormal. Section 4 of this report will discuss the adjustment of the Global model parameters to fit the measured cumulative distribution.

3.4.4 Crg_cal.xls (file)

Crg_cal.xls is an EXCEL® spreadsheet file which contains all the calibration data for the CRG. Each column consists of a dated heading which corresponds to the date the calibration was performed. This heading is followed by the CRG's output reading, for each 50 ml incremental input, in the range from zero to 500 ml. The calibration data is loaded into a rainrate.xls or rainrate.xls program, whose date precedes the date of the data file that was called from these programs. The calibration data is used to transform the CRG readings to actual rain accumulation.

3.4.7 Macros

Macros were developed for the rain.xls and rainrate.xls, programs to access data files by clicking on the "Get Files" button. The macros are similar to all the programs (see Appendix 4) for the macro on the rain.xls program.

3.5 Areas of Improvement

The Visual Basic 3.0® "decomp5.exe" program described in Section 3.3 needs to be modified in order to facilitate generating data files for the software in the preceding sections. Following is a list of possible changes which would be helpful.

- access the rv0 files with a pop-up "Select a File" dialog box.
- select which software the data files are designated for - the format for the name of the data file will be automatically updated, the set of data would be automatically selected, and the file will be transferred to the appropriate designation when the program is ended.
- select the time span if necessary, and write in the start time only - the file header (control parameters) in the first row would be automatically entered here.
- show the file date for all windows in this program.
- access the data up to the 24 hour mark.

4 Rain Rate Statistics

The previous sections describe the methodology used in determining rain rate. For each rain event, the capacitive rain gauge at the APT measures the rain accumulation, and using the software discussed in this report, the rain rate were extracted from these measurements. This section will discuss the accuracy of one of the rain rate prediction models which is available for satellite system designers.

Two rain rate prediction models are commonly used, the Global Model developed by Robert Crane[1][2], and the ITU-R Model[2][3]. Each has its own set of parameters derived with its statistical methodologies and globally divided homogeneous rain rate regions. Rain events have been collected globally for decades, but accumulation only (and not rain rate) was advocated, where the sampling of the rain events was inadequate to determine the rain rate. With the emergence of satellite communication frequencies in the Ka band, where the dominate factor in signal degradation is the rain rate, the need for accurate rain rate prediction models is now more critical. Therefore, the models' prediction performance, based on empirically derived rain rates from inadequate sampling rates (in minutes), may need to be further investigated. Crane has done extensive studies of rain rates with appropriate measuring apparatus (with higher sampling rates) in region D, which extends from the Eastern seaboard to the Midwestern region of the continental United States. Recent studies in this region resulted in further subdivision into three regions, D1-D3. Southern New Mexico encompasses Global Model's dry climate region, as designated as region F. This report will analyze the accuracy of Crane's Global Model pertaining to region F.

4.1 Global Rain Rate Model

Crane[2] presents criteria for the parameters on the Global model, which sets boundaries on the model's 12 worldwide climate zones. He stated that each zone would have location-to-location rain rate variability, which is comparable to the year-to-year variation at any

given location. This statement is the most powerful in his article, yet Crane did not elaborate on this. He suggests that this is a random process which is ergodic in the mean. Ergodic implies that the statistics of the rain rate is time invariant, thus we have a stationary process. Note that this is an assumption he made without proving that the random process is stationary. With ergodicity in the mean, statistics can be derived by the ensemble averages of the rain rate at each location, or equivalently from time average at any location within the zone. This is convenient since the yearly statistics for rain rate are not sufficient. In the article, Crane stated one would need a minimum of ten to twenty one-year distributions at a site to adequately estimate true distribution. The data which are available consist of empirical distributions for periods from two months to six years. As a final note on this matter, time will be the dominating factor in proving the validity of Crane's assumption as more data is collected over the years. In the conclusion of his article, he recognizes that climate regions may need further subdivisions, since statistics of the rain rate are beginning to show significant differences among locations within a climate region.

There are two closed-form probability distribution models for the Global Model, the three-parameter lognormal rain rate model, and the two-component rain rate model with five parameters. The two-component model addresses the contribution to high rain rate volume cells and the light intensity rain surrounding the cells separately, whereas the three-parameter lognormal model does not separate the two types of rain intensity.

4.1.1 Three-Parameter Lognormal Model

The three-parameter lognormal model is the basic model that describes rain rate cumulative distribution with a number of authors[1], including the ITU Model. To empirically fit this model with the observed rain rate data, the probability of rain (P_L) is assumed (empirically fit the measured rain rate distribution), and the remaining two parameters of the model are obtained by least-square regression analysis. The three-parameter lognormal model for the empirical rain rate distribution function is [2]:

$$P(r \geq R) = \frac{P_L}{2} \operatorname{erfc}\left(\frac{\ln(R) - \ln(R_L)}{\sqrt{2} S_L} \right)$$

where $P(r \geq R)$ = probability that observed rain rate "r" exceeds specified rain rate "R"

P_L = probability of rain

R_L = median rain rate

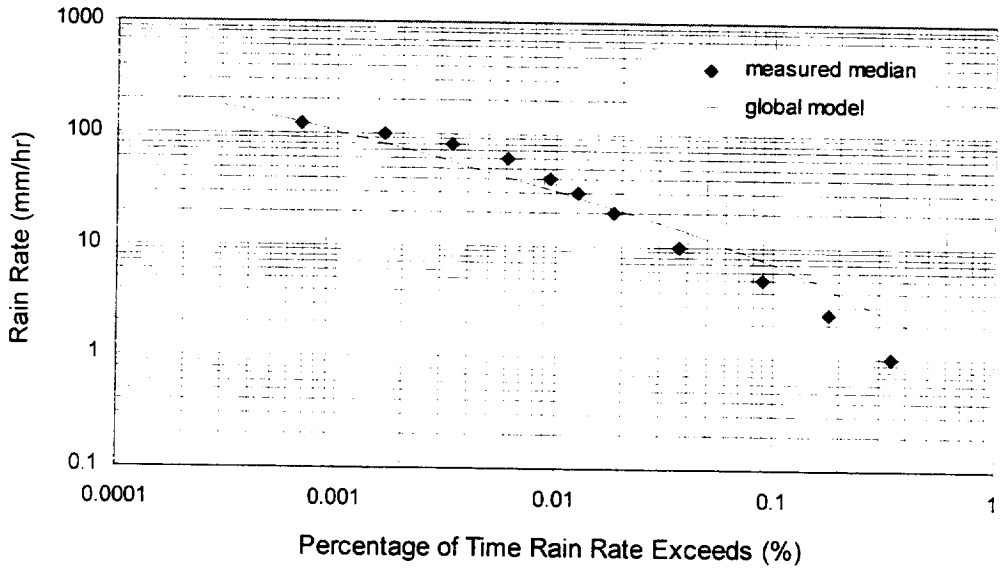
S_L = standard deviation of the natural logarithm

The following table[2] lists the parameter values for the Global three-parameter lognormal model.

Table 5 Parameter Values for the Global Three-Parameter Lognormal Model

Global Climate Zone	P_L % probability of rain	R_L mm/hr median rain rate	S_L standard deviation of the natural logarithm
A	2.55	0.18	1.50
B	11.91	0.11	1.66
B1	11.91	0.08	1.69
B2	11.91	0.12	1.69
C	11.91	0.18	1.60
D1	11.93	0.23	1.59
D2	5.89	0.79	1.39
D3	4.02	1.97	1.22
E	5.04	2.17	1.29
F	3.99	0.19	1.69
G	11.37	1.41	1.32
H	7.05	2.74	1.34

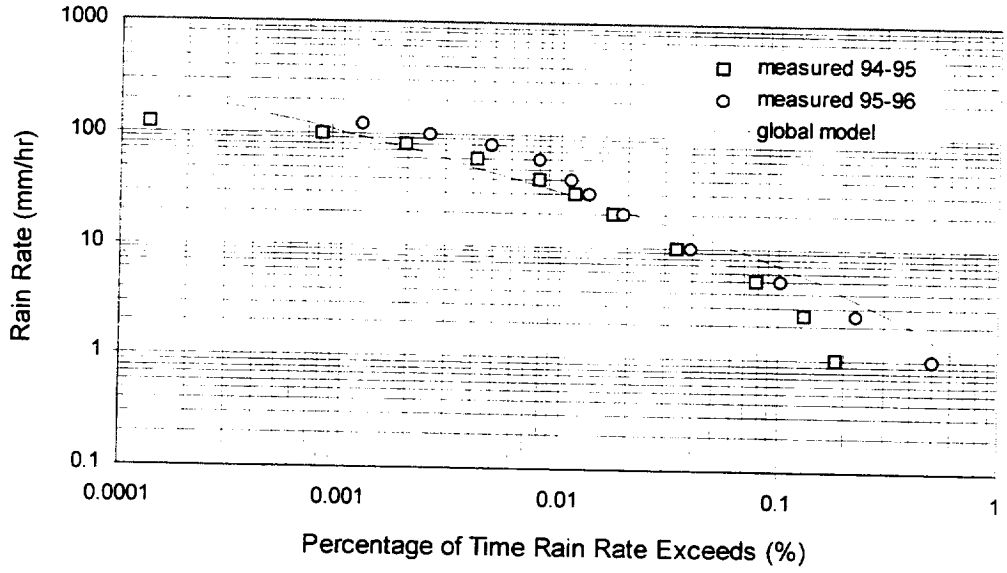
The climate region for New Mexico APT site is zone F. The following figure displays the predicted rain rate distribution, using the parameters from the above table in climate zone F, versus the measured distribution (two year average) as shown in Figure 7.



Global Three-Parameter Lognormal Model $P_L = 3.99$ $R_L = 0.19$ $S_L = 1.69$
verses measured median rain rate distribution (2 year average - 1995,96)

Figure 8 Rain Rate Distribution for Three-Parameter Lognormal Model Using Crane's Parameters (2 Year Average)

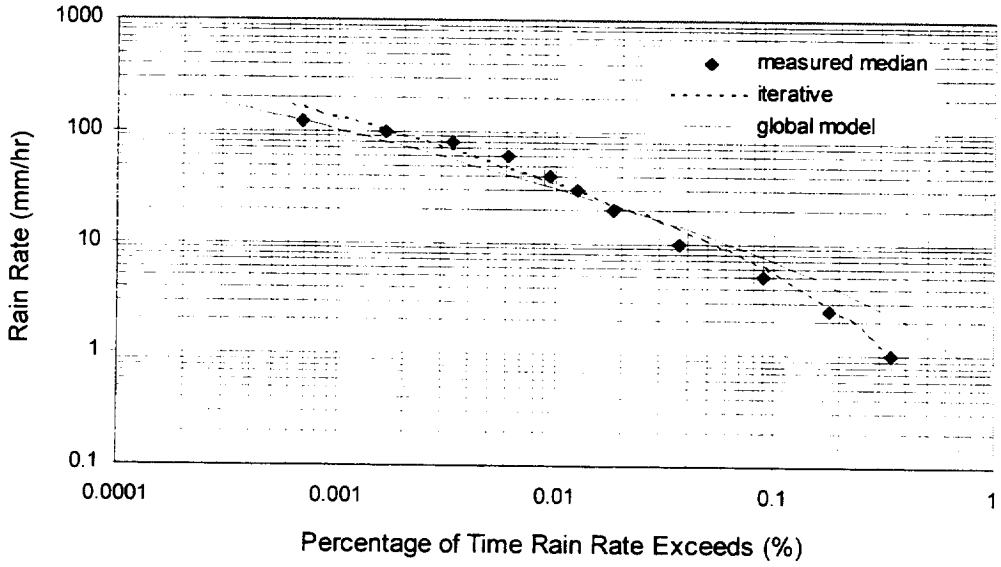
The above figure indicates that the model predicts a higher percentage of time the rain rate value is exceeded for low rain rate values, and a lower percentage for high rate values. The comparison is made against the average (yearly) measured values of the rain rate events for the period of October 1994 through September 1996. As it was stated in section 4.1, one would need ten to twenty one-year distributions at a site to adequately estimate the true distribution. The figure below compares the model with each of the two year measured distributions.



Global Three-Parameter Lognormal Model $P_L = 3.99$ $R_L = 0.19$ $S_L = 1.69$
verses measured median rain rate distribution (1995,96)

Figure 9 Rain Rate Distribution for Three-Parameter Lognormal Model Using Crane's Parameters

The above figure has the same prediction characteristics as the measured median distribution shown in the Figure 8. There are no confidence intervals provided by Crane for the prediction model; therefore, one cannot argue that the prediction model does *not* fit the measured median distribution. But one can adjust the model's parameters for a *better* fit in the least square error sense. The procedure discussed at the beginning of this section is to assume the probability of rain (P_L), and the remaining two parameters of the model are obtained by least-square regression analysis. Essentially, for best fit, one would iterate P_L for least-square error and iterate the remaining two parameters. This was accomplished with Mathcad® by stepwise iterating the parameters for least-square error fit. First P_L was adjusted, followed by R_L and finally S_L. Mathcad®'s program listing is shown in Appendix 1. The results are shown in the following figure.

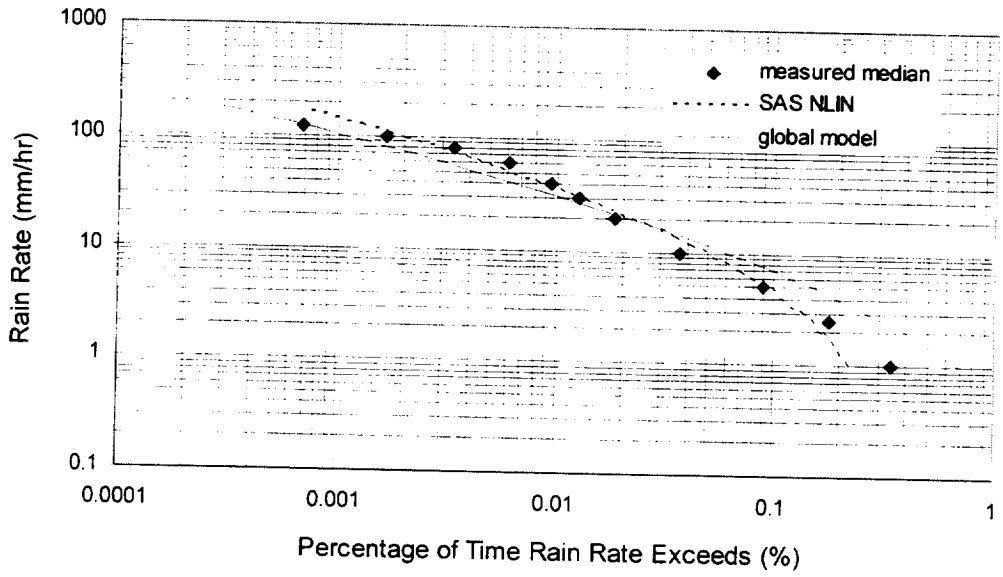


Global Three-Parameter Lognormal Model
Stepwise Iteration - Mathcad® $P_L = 2.33$ $R_L = 0.201$ $S_L = 1.85$
verses measured median rain rate distribution (2 year average - 1995,96)

Figure 10 Rain Rate Distribution for Three-Parameter Lognormal Model
Least-Square Error Fit - Mathcad®

Stepwise iteration for least-square error improved the model's fit with the average measured values for all rain rate values below the 120 mm/hr point rain rate. Another statistical procedure is used to least-square fit the model, gradient descent on all three parameters simultaneously. This was performed using SAS®'s NLIN procedure. The model's prediction equation was entered into this program, along with the partial derivatives of the equation with respect to each of the parameters. The partial derivative of a Gaussian distribution was evaluated by using Leibniz rule. The program listing is in Appendix 2.

The following figure is the prediction model fit using the parameters evaluated by SAS®.



Global Three-Parameter Lognormal Model
Gauss-Newton Method - SAS NLIN $P_L = 1.02$ $R_L = 0.484$ $S_L = 1.732$
verses measured median rain rate distribution (2 year average - 1995,96)

Figure 11 Rain Rate Distribution for Three-Parameter Lognormal Model Least-Square Error Fit - SAS®

The above figure indicates the rain rate prediction model, whose parameters were evaluated using SAS®'s NLIN procedure, does not fit the measured distribution as well as the stepwise iteration in Mathcad® at the low rain rate region of the distribution. Neither did the fit agree with the high rain rate region. Yet for theoretical optimal minimum least-square fit, SAS®'s gradient descent procedure is optimal. Comparing the above two figures, the parameters evaluated by SAS®, resulted in a better fit in the 100 mm/hr to 10 mm/hr rain rate region. Other parameter adjustments were performed in the NLIN procedure, such as having P_L as a constant, and evaluating the remaining two components. The results of these adjustments did not fit the model for all the rain rates, nor was it an improvement over the initial analysis. Other curve fitting models within the NLIN procedure were used; all converged to the same parameter values. It should be

noted that SAS® NLIN procedure *assumes* the distribution for $P(r \geq R)$ at each R is identical. Although we only have two years of data in which we cannot validate this claim, studies have indicated there is variability in the distributions[2].

Crane has indicated that the three parameter lognormal model, through various curve-fitting procedures, could not fit the rain rate distribution over the full range of rain rate values needed for modeling attenuation by rain. To provide a better fit between measured and modeled attenuation distribution, Crane claims the two-component model outperforms the three-parameter lognormal model.

4.1.2 Two-Component Model

The two-component model consists of what the name implies, two distribution components, which Crane designated a cell component and a debris component. The cumulative distribution for the cell component is exponential, which represents small-scale spatial structures of short duration. Wider spatial structures are represented by the debris component, whose cumulative distribution is lognormal. The joint cumulative distribution for cells and debris is assumed to be independent. The two-component model for the empirical rain rate distribution function is [1]:

$$P(r \geq R) = P_C(r \geq R) + P_D(r \geq R)$$

$$P_C(r \geq R) = P_C e^{-R/R_C}$$

$$P_D(r \geq R) = P_D N\left(\frac{\ln R - \ln R_D}{S_D}\right)$$

where $P(r \geq R)$ = probability that observed rain rate exceeds specified rain rate R for the cell component

$P_C(r \geq R)$ = cumulative distribution function for volume cells

P_C = probability of cell

R_C = average rain rate in cell

for the debris component

$P_D(r \geq R)$ = cumulative distribution function for debris

N = normal distribution function

P_D = probability of debris

R_D = median rain rate in debris (calculated from average of natural rain rate)

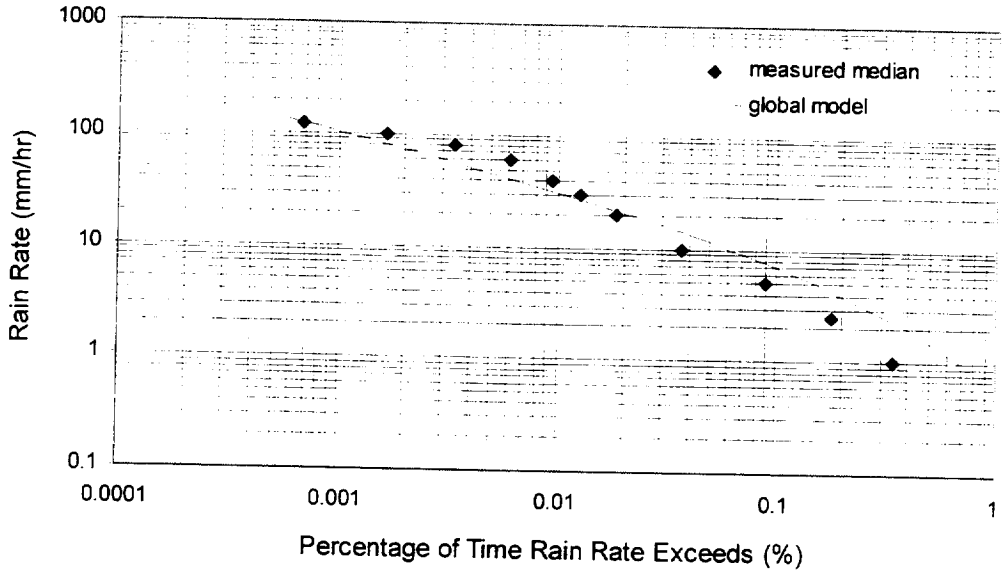
S_D = standard deviation of natural logarithm of rain rate

The table[2] below lists the parameter's values for the two-component rain rate prediction model in region F.

Table 6 Parameter Values for the Global Two-Component Model

Global Climate Zone	P_C %	R_C mm/hr	P_D %	R_D mm/hr	S_D
A	0.00009	3.45	2.27	0.21	1.48
B	0.02301	14.30	10.76	0.18	1.44
B1	0.00901	11.11	12.00	0.09	1.61
B2	0.02322	17.49	12.00	0.18	1.48
C	0.03317	19.81	12.00	0.19	1.31
D1	0.02612	23.20	8.19	0.46	1.34
D2	0.03127	14.29	9.27	0.48	1.48
D3	0.04796	17.05	4.00	1.97	1.21
E	0.22423	23.24	5.25	2.02	1.25
F	0.00483	8.26	6.95	0.10	1.81
G	0.02768	50.47	9.82	1.82	1.20
H	0.04751	35.43	7.00	2.47	1.49

The following figure displays the predicted rain rate distribution, using the parameters from the above table in climate zone F, versus the measured distribution (two year average) as shown in Figure 7.



Global 2-C Model $P_D = 6.95$ $R_D = 0.10$ $S_D = 1.81$ $P_C = 0.00483$ $R_C = 8.26$
verses measured median rain rate distribution (2 year average - 1995,96)

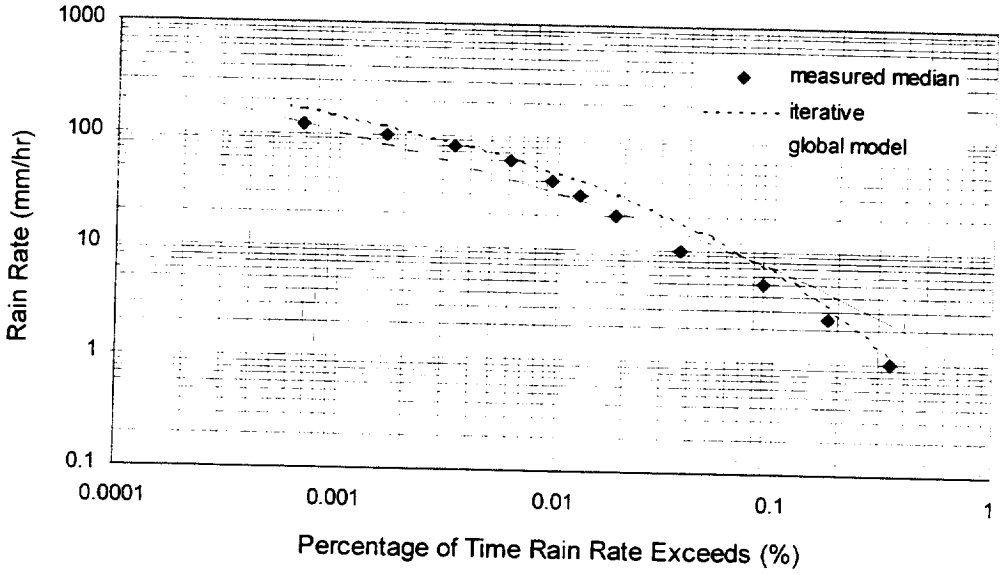
Figure 12 Rain Rate Distribution for Two-Component Model Using Crane's Parameters (2 Year Average)

The initial parameters for the two-component model resulted in a distribution comparable to the three-parameter lognormal shown in Figure 8 in the previous section. The procedure[1] to estimate the two-component parameters for empirically fitting the prediction model to the measured rain rates is as follows:

- The wider spatial structures are represented by the debris component, whose cumulative distribution is lognormal for the rain rates below 40 mm/hr region. Use Mathcad® stepwise iteration to determine the P_D, R_D , and S_D parameters. Mathcad®'s program listing is in Appendix 1.

- The cumulative distribution for the cell component is exponential, which represents the high rain rate region, above 40 mm/hr. In this region, the difference between the tail of the lognormal distribution and the median measured distribution was used to fit

(by least -squares) an exponential distribution. Use Mathcad® stepwise iteration to determine the P_C, and R_C parameters.



Global 2-C Model

Stepwise Iteration - Mathcad® $P_D = 2.33$ $R_D = 0.201$ $S_D = 1.84$ $P_C = 0.021$ $R_C = 29.87$
verses measured median rain rate distribution (2 year average - 1995,96)

Figure 13 Rain Rate Distribution for Two-Component Model
Least-Square Error Fit - Mathcad®

The empirical fit for the two-component model does not appear to have any improvement over the three-component model. The overall root mean square (rms) error between the empirical fit and the median distribution is approximately the same for the two models.

Evaluating the parameters for the lognormal component in the two-component model in SAS®'s NLIN procedure (see program listing in Appendix 2) resulted in an empirical fit whose exceedence value at the low rain rate was lower than the measured median value, which was the same result as for the three-parameter model.

4.2 Attenuation Statistics

Rain attenuation prediction models[1] for slant paths (Earth-space) use rain rate R as one of the models' parameters. Other parameters include the following:

- 0°C isotherm height, H_0, where any precipitation above this height is frozen. High frequencies propagating through frozen precipitation suffers little loss. Measurements have shown there is a tendency for a linear relationship between H_0 and R at high rain rates. As was discussed in Section 4.1.2, there is an approximate linear relationship between R and the natural logarithm of $P(r \geq R)$ at high rain rates in the two-component model Therefore, an estimation of rain height H_R for $P(r \geq R)$ between 0.001 and 1% can be interpolated by

$$H_R = a + b\ln(P)$$

  where P is $P(r \geq R)$ and H_R is also dependent on the Earth's latitude.

- Coefficients of specific attentuation for horizontal and vertical polarization, κ and α. These parameters are used in a power-law relationship between specific attenuation and rain rate. Specific attenuation depends on the parameters of the rain drop and the properties of the electromagnetic wave propagating through a volume of rain at a point in space. The properties includes the polarization of the wave and its frequency, thus κ and α are dependent on these properties. The specific attenuation at a point equation is:

$$\gamma(R) = \kappa R^{\alpha}$$

The following table[3] lists the parameters of the specific attenuation at a point.

Table 7 Coefficients of Specific Attenuation for Horizontal and Vertical Polarizations

Frequency GHz	κ_H	κ_V	α_H	α_V
10	0.0101	0.0089	1.28	1.26
20	0.0751	0.0691	1.10	1.07
30	0.187	0.167	1.02	1.00

Note: 20 GHz and 27 GHz beacons are both vertically polarized.

The specific attenuation at a point equation is modified to determine the median rain rate along a horizontal path of length D. This model has two exponential functions, each spanning a proportion of the path length, determined by a function of rain rate, $\delta(R)$ in km. The resulting model for attenuation on a *horizontal* path is shown next, followed by a multiplier for a slant path conversion:

$$A_T(R,D) = \gamma(R)\left(\frac{e^{y\delta(R)}-1}{y} + \frac{e^{zD}-e^{z\delta(R)}}{z}e^{\alpha B}\right) \qquad \delta(R) < D < 22.5$$

$$A_T(R,D) = \gamma(R)\left(\frac{e^{y\delta(R)}-1}{y}\right) \qquad 0 < D < \delta(R)$$

where A_T = horizontal path attenuation (dB)

R = rain rate (mm/hr)

D = path length (km)

$\gamma(R)$ = specific attenuation, = κR^{α} (dB/km)

and the remaining coefficients are empirical constants:

$$B = 0.83\text{-}0.17\ln(R)$$

$$c = 0.026\text{-}0.03\ln(R) \quad (km^{-1})$$

$$\delta(R) = 3.8\text{-}0.6\ln(R) \quad (km^{-1})$$

$$u = \frac{B}{\delta(R)} + c \quad (km^{-1})$$

$$y = \alpha u \quad (km^{-1})$$

$$z = \alpha c \quad (km^{-1})$$

The horizontal path D is the projection of the slant path, which is a function of the isotherm height, H_R and the elevation angle, ζ. The following equation computes the conversion.

$$D = \frac{H_R - H_S}{\tan\zeta}$$

where H_S is the station height (APT at White Sands is 1.459 km).

The above prediction attenuation analysis is for terrestrial (horizontal) path. Conversion to the slant path is given in the following equation.

$$A_S = \frac{L}{D} A_T(R.D)$$

where L is the slant length, which is computed by the following equation.

$$L = \sqrt{(H_S + R_E)^2 \sin^2\zeta + 2R_E(H_R - H_S) + H_R^2 - H_S^2} - (H_S + R_E)\sin\zeta$$

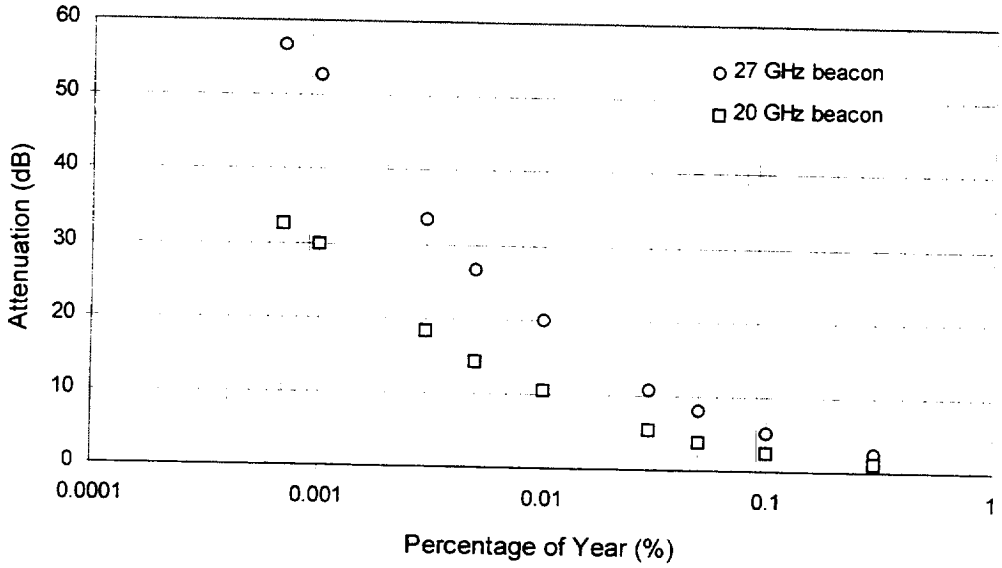
where R_E is the effective Earth's radius.

The following table gives the results of the attenuation prediction. Computations were performed on Mathcad®, and the program listing is in Appendix 1.

Table 8 Rain rate Attenuation Prediction versus Percentage of Year

Year	Attenuation Prediction (dB)		Isotherm Height	Surface Projection
%	20 GHz	27 GHz	H_R (km)	D (km)
0.0007	32.43	56.68	5.36	3.05
0.001	29.80	52.68	5.28	2.99
0.003	18.17	33.31	5.04	2.80
0.005	14.32	26.73	4.93	2.71
0.01	10.39	19.89	4.77	2.59
0.03	5.40	10.82	4.53	2.40
0.05	3.88	7.96	4.42	2.31
0.1	2.41	5.13	4.27	2.19
0.3	1.04	2.36	1.02	2.01

The figure below is a plot of the attenuation results from Table 8. Presently, the measured attenuation levels throughout 1995 and 1996 have not been tabulated at NMSU. It would be interesting to see the comparison between measured and predicted attenuation levels, which would validate the attenuation prediction model described in this section. It should be noted that the receiver sensitivity at the APT site is only reliable to approximately -20 dB. Below this level, the receiver may lose lock on the beacon signal, and the accuracy of the attenuation reading is degraded[3].



Beacon Signal Attenuation distribution

Figure 14 Signal Attenuation

5 Summary / Conclusion

This report discusses the methodology used in determining empirical rain-rate distributions for Southern New Mexico in the vicinity of White Sands APT site. Rain-rate distributions are valuable to satellite system designers in determining link margins for operating frequencies above 10 GHz. These high frequencies may be common in the near future, with the need to expand the frequency spectrum beyond the existing saturated spectrum. The previous section is an example how rain rate statistics are used in attenuation models. These models gives system designers the expected link availability in terms of percentage of time in a given year. Since these models are derived with statistics, and with little accurate rain rate data available, research in determining the accuracy of these models is necessary by combining yearly measured attenuation levels and measured rain rate. With accurate attenuation models, designers can predict attenuation due to rain for *all* frequencies above 10 GHz.

Sections 2 and 3 of this report discussed the hardware and the software developed which were necessary to extract rain rate from the rain accumulation data collected at White Sands APT site. Two full years (1995 and 1996) of measured rain rate were used to determine the accuracy of published rain rate models. This report only compares the measured rain rate to Robert Crane's Global models, the three-parameter lognormal and the two-component model. Initially, with two years of measured data to compare with, the model's distribution did not appear to fit the measured median rain rate distribution. Although this may be a premature statement, since only two years of data were collected for determining yearly statistics, and no confidence intervals were given for the model's distribution, there appears to be a similar trend in that neither prediction model fits the measured median distribution. As shown in Section 4, the models predict a higher rain rate in the low rain rate region of the distribution and a lower rain rate for the high rain rate region.

Two curve fitting techniques were used to adjust the models' parameters for a best fit with the median distribution. Both use least square regression analysis. One technique iterates one parameter at a time, the other iterates all the parameters with a gradient descent procedure. An algorithm was written in Mathcad® to iterate each parameter separately (stepwise) for a least square error fit. The three-parameter lognormal has three parameters to iterate. Initially Crane's region F parameters were used. First P_L was iterated for minimum least square error, then R_L and S_L followed, each using the optimal parameter evaluated beforehand. Similar calculations were performed on the two-component model. One of the components which represents low rain rate has a lognormal distribution, and its parameters were adjusted with the same procedure as in the three-parameter lognormal model. The other component, an exponential distribution which represents high rain rates or rain cells, had its parameter evaluated as the least square error difference of the median distribution and the optimal lognormal component. Using Crane's parameters initially, P_C was evaluated first, then R_C with the optimal P_C value. Stepwise parameter adjustments for both prediction models resulted in a better fit

for *all* rain rate within the measured median distribution, as compared with the gradient descent procedure.

SAS®'s nonlinear regression analysis (NLIN) was used for the gradient descent procedure. This procedure is the optimal procedure to use, if *all* the rain rate distribution parameters were available. The assumption made in this report was that the distribution of the variability of the percentage of time rate exceeded for each of the rain rates are the *same*. Observing Figure 9, with only two data points for each of the yearly measured rain rates, the difference between the two years has a higher disparity at the extreme ends of the distribution. In the middle of the distribution, the difference between yearly measured rain rates is small. SAS® adjusted the parameters such that in this region the SAS® NLIN's procedure provided a better fit than Mathcad®'s stepwise procedure, as shown in Figure 11. Thus knowing the variability of the percentage of time rate exceeded for each of the rain rates, one can determine the weight of each the median rain rates in SAS® NLIN procedure, thus providing a better fit. One cannot determine this weight with only two data points. Ten to twenty years of collected data is needed to determine the variability distribution for each rain rate. Robert Crane has done extensive research on evaluating variability distributions[2], and has determined that this distribution is also lognormal.

It is imperative to continue to collect rain rate data for at least ten years, to determine an accurate rain rate prediction model in Southern New Mexico. There is also an underlying *assumption* for the preceding statement -- the wide area surrounding White Sands APT site in Crane's region F -- is homogenous. That is, the rain rate average over a long period of time is the same at all points within the region.

6 References

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8 Appendices

1 Mathcad® Program Listings

- 1.1 Three-Parameter Lognormal Model
- 1.2 Two-Component Model
- 1.3 Attenuation Model

2 SAS® Program Listings

- 2.1 Three-Parameter Lognormal Model
- 2.2 Two-Component Model

3 Rain Rate Data

4 Macro

- 4.1 Mac_rain.xls
- 4.2 Mac_rate.xls

5 ACTS's Directory and File Paths

1.1 Three-Parameter Lognormal Model

1.1 Three Parameter Lognormal Model

This program evaluates the parameters for the lognormal rain-rate prediction model, by step-by-step least squares iteration.

Exceed $_m$ is the measured percentage of time the rain rate is exceeded for the aveage of years 95,96.

Rate is the point rain rate (independent variable).

$x := 1..11$

Measured Values

dependent variable

Exceed $_{m_x}$

0.3443
0.1773
0.0894
0.369
0.0185
0.0126
0.0096
0.0061
0.0034
0.0017
0.0007

independent variable

Rate $_x$

1
2.5
5
10
20
30
40
60
80
100
120

Parameters

$y := 0..100$

Iterate P L $P_{L_y} := 1.99 - \frac{y}{50}$

Given $R_L := 0.19$

$S_L := 1.69$

lognormal rain-rate prediction model $lognorm_{x,y} := \frac{P_{L_y}}{2}\left[1 - erf\left(\frac{\ln(Rate_x) - \ln(R_L)}{2 \cdot S_L}\right)\right]$

least square error $error_y := \sum_x \left(lognorm_{x,y} - Exceed_{m_x}\right)^2$

$n_y := y$ $A := csort(augment(error, n), 0)$ $A_{0,1} = 17$ $P_L := 1.99 - \frac{A_{0,1}}{50}$

Result for P L $P_L = 2.33$

$y := 0..100$

Iterate R L $R_{L_y} := 0.16 - \frac{y}{1000}$

Given $P_L = 2.33$

$S_L := 1.69$

lognormal rain-rate prediction model $lognorm_{x,y} \quad \frac{P_L}{2} \cdot 1 \cdot erf\left(\frac{\ln Rate_x - \ln R_{L_y}}{2 \cdot S_L}\right)$

least square error $error_y \quad \sum_x lognorm_{x,y} - Exceed_x^{\,2}$

$n_y \quad y \quad A \quad csort(augment(error, n), 0) \qquad A_{0,1} = 41 \qquad R_L \quad 0.16 \cdot \frac{A_{0,1}}{1000}$

Result for R L $R_L = 0.201$ $y \quad 0..200$

Iterate S L $S_{L_y} \quad 1 \cdot \frac{y}{20}$ Given $P_L = 2.33$

$R_L = 0.201$

lognormal rain-rate prediction model $lognorm_{x,y} \quad \frac{P_L}{2} \cdot 1 \cdot erf\left(\frac{\ln Rate_x - \ln R_L}{2 \cdot S_{L_y}}\right)$

least square error $error_y \quad \sum_x lognorm_{x,y} - Exceed_x^{\,2}$

$n_y \quad y \quad A \quad csort(augment(error, n), 0) \qquad A_{0,1} = 17 \qquad S_L \quad 1 \cdot \frac{A_{0,1}}{20}$

Result for S L $S_L = 1.85$

rms error $x \quad 1..11 \qquad lognrm_x \quad \frac{P_L}{2} \cdot 1 \cdot erf\left(\frac{\ln Rate_x - \ln R_L}{2 \cdot S_L}\right)$

$rmserror \quad \frac{1}{11} \cdot \sum_x lognrm_x - Exceed_x^{\,2} \qquad rmserror = 0.104328$

rms error for SAS NLIN procedure $P_L \quad 1.02 \quad R_L \quad 0.484 \quad S_L \quad 1.732$

$x \quad 1..11 \qquad lognrm_x \quad \frac{P_L}{2} \cdot 1 \cdot erf\left(\frac{\ln Rate_x - \ln R_L}{2 \cdot S_L}\right)$

$rmserror \quad \frac{1}{11} \cdot \sum_x lognrm_x - Exceed_x^{\,2} \qquad rmserror = 0.098923$

1.2 Two-Component Model

1.2 Two-Component Model

This program evaluates the parameters for the 2-C rain-rate prediction model, by step-by-step least squares iteration for the lognormal and exponental component.

$Exceed_m$ is the measured percentage of time the rain rate is exceeded for the aveage of years 95,96.

Rate is the point rain rate (independent variable).

$x \quad 1..11$

Measured Values

dependent variable — independent variable

$Exceed_{m_x}$	$Rate_x$
0.3443	1
0.1773	2.5
0.0894	5
0.369	10
0.0185	20
0.0126	30
0.0096	40
0.0061	60
0.0034	80
0.0017	100
0.0007	120

Parameters

$y \quad 0..100$

Iterate PD $P_{D_y} \quad 1.99 - \frac{y}{50}$

Given $R_D \quad 0.19$

$S_D \quad 1.69$

range for lognormal compone nt - debris $x \quad 1..7$

lognormal component $lognorm_{x,y} \quad \frac{P_{D_y}}{2} \cdot \left(1 - erf\left(\frac{\ln(Rate_x) - \ln(R_D)}{2 \cdot S_D}\right)\right)$

least square error $error_y \quad \sum_x lognorm_{x,y} - Exceed_{m_x}^2$

$n_y \quad y \quad A \quad csort(augment(error, n), 0) \quad A_{0,1} = 17 \quad P_D \quad 1.99 - \frac{A_{0,1}}{50}$

Result for PD $P_D = 2.33$

$y \quad 0..100$

Iterate RD $R_{D_y} \quad 0.16 - \frac{y}{1000}$

Given $P_D = 2.33$

$S_D \quad 1.69$

lognormal component $lognorm_{x,y} := \frac{P_D}{2} \cdot \left(1 - erf\left(\frac{\ln(Rate_x) - \ln(R_{D_y})}{2 \cdot S_D}\right)\right)$

least square error $error_y := \sum_x \left(lognorm_{x,y} - Exceed_{m_x}\right)^2$

$n_y := y \quad A := csort(augment(error, n), 0) \quad A_{0,1} = 4i \quad R_D := 0.16 \cdot \frac{A_{0,1}}{1000}$

Result for R D $R_D = 0.201$

$y := 0..200$

Iterate S D $S_{D_y} := 1 \cdot \frac{y}{200}$

Given $P_D = 2.33$

$R_D = 0.201$

lognormal component $lognorm_{x,y} := \frac{P_D}{2} \cdot \left(1 - erf\left(\frac{\ln(Rate_x) - \ln(R_D)}{2 \cdot S_{D_y}}\right)\right)$

least square error $error_y := \sum_x \left(lognorm_{x,y} - Exceed_{m_x}\right)^2$

$n_y := y \quad A := csort(augment(error, n), 0) \quad A_{0,1} = 168 \quad S_D := 1 \cdot \frac{A_{0,1}}{200}$

Result for S D $S_D = 1.84$

range for exponental componen t $x := 8..11$

$lognrm_x := \frac{P_D}{2} \cdot \left(1 - erf\left(\frac{\ln(Rate_x) - \ln(R_D)}{2 \cdot S_D}\right)\right)$

Parameters $y := 0..1000$

Iterate P C $P_{C_y} := .01 \cdot \frac{y}{1000}$

Given $R_C := 30$

exponential component $exponent_{x,y} := P_{C_y} \cdot \exp\left(\frac{Rate_x}{R_C}\right)$

least square error $error_y := \sum_x \left(exponent_{x,y} - Exceed_{m_x} - lognrm_x\right)^2$

$n_y := y \quad A := csort(augment(error, n), 0) \quad A_{0,1} = 18 \quad P_C := 0.01 \cdot \frac{A_{0,1}}{1000}$

Result for PC $P_C = 0.028$

$y := 0..100$

Iterate RC $R_{C_y} := 29 \cdot \frac{y}{100}$

Given $P_C = 0.028$

exponential component $exponent_{x,y} := P_C \cdot \exp\left(\frac{Rate_x}{R_{C_y}}\right)$

least square error $error_y := \sum_x \left(exponent_{x,y} - Exceed_{m_x} - lognrm_x\right)^2$

$n_y := y \quad A := csort(augment(error, n), 0) \quad A_{0,1} = 87 \quad R_C := 29 \cdot \frac{A_{0,1}}{100}$

Result for RC $R_C = 29.87$

rms error

$x := 1..11 \quad expon_x := P_C \cdot \exp\left(\frac{Rate_x}{R_C}\right)$

$rmserror := \frac{1}{11} \cdot \sum_x \left(lognrm_x - expon_x - Exceed_{m_x}\right)^2$

rmserror = 0.15067

3.1 Attenuation Model

3.1 Attenuation Model

Guess values: $a := 1$

$b := 1$

Given

$a - b \cdot \ln(0.001) = 5.28$

$a - b \cdot \ln(1.0) = 3.76$

$\begin{pmatrix} aval \\ bval \end{pmatrix} := \text{Find}(a, b)$

Results: $aval = 3.76$ $a := aval$

$bval = 0.220043$ $b := bval$

$n := 1 .. 9$

Probabilities: P_n

P_n
.0007
.001
.003
.005
.01
.03
.05
.1
.3

Rain Height (km) $H_{R_n} := a - b \cdot \ln(P_n)$

H_{R_n}	P_n
5.358484	0.0007
5.28	0.001
5.038259	0.003
4.925855	0.005
4.773333	0.01
4.531592	0.03
4.419189	0.05
4.266667	0.1
4.024925	0.3

White Sands APT surface height above sea level (km) $H_s := 1.459$

Effective Earth's radius (km) $R_E := 8500$

NM APT Elevation angle (radians) $\zeta := \frac{2 \cdot \pi}{360} \cdot 51.98$

Evaluate slant distance D

For elevation ange greater or equal to: $D_n \quad \frac{H_{R_n} \quad H_S}{\tan(\zeta)}$

D_n	P_n
3.048803	0.0007
2.987441	0.001
2.798436	0.003
2.710554	0.005
2.591305	0.01
2.4023	0.03
2.314417	0.05
2.195168	0.1
2.006163	0.3

Derive pain rate R from the three-parameter lognormal prediction model

Iterate on a given probability in % (prob) with initial start value (start)

$P_L \quad 2.33 \qquad R_L \quad 0.201 \qquad S_L \quad 1.85$

$x \quad 0..100 \qquad prob \quad 0.0007 \qquad start \quad 114 \qquad Rate_x \quad start \cdot \frac{x}{100}$

$$lognorm_x \quad \frac{P_L \cdot 1 \quad erf\left(\frac{\ln Rate_x \quad \ln R_L}{2 \cdot S_L}\right)}{2}$$

$absdiff_x \quad prob \quad lognorm_x$

$n_x \quad x \quad A \quad csort(augment(absdiff, n), 0) \qquad A_{0.1} = 81 \qquad Rate \quad start \cdot \frac{A_{0.1}}{100} \qquad Rate = 114.81$

Results of iteration

$n \quad 1..9$

P_n	$Rate_n$
0.3	1.63
0.1	4.82
0.05	8.51
0.03	12.44
0.01	25.99
0.005	39.6
0.003	53.1
0.001	95.78
0.0007	114.81

Evaluate Attenuation (statistical)

Note : 20 GHz and 27 GHz are vertical polarized.

Specific attenuation coefficients for horizontal and vertical polarization

$\kappa_{V27} := 0.167 \quad \kappa_{V20} := 0.069$

$\alpha_{V27} := 1.00 \quad \alpha_{V20} := 1.07$

Compute A(R,D) for 20 GHz

$\delta(R) := 3.8 - 0.6 \cdot \ln(Rate_n)$

$c_n := 0.026 - 0.03 \cdot \ln(Rate_n)$

$B_n := 0.83 - 0.17 \cdot \ln(Rate_n)$

$u_n := \left(\frac{B_n}{\delta(R)}\right)^{c_n}$

$y_n := \alpha_{V20} \cdot u_n$

$z_n := \alpha_{V20} \cdot c_n$

$\gamma(R) := \kappa_{V20} \cdot Rate_n^{\alpha_{V20}}$

$A_{T_n} := \text{if}\left(\delta(R) < D_n, \gamma(R) \cdot \frac{e^{y_n \cdot \delta(R)} - 1}{y_n}, \frac{e^{z_n \cdot D_n} - e^{z_n \cdot \delta(R)}}{z_n} \cdot e^{\alpha_{V20} \cdot B_n} \cdot \gamma(R) \cdot \frac{e^{y_n \cdot \delta(R)} - 1}{y_n}\right)$

$\delta(R)$	D_n
3.506852	3.048803
2.856336	2.987441
2.515255	2.798436
2.28745	2.710554
1.845373	2.591305
1.592703	2.4023
1.416694	2.314417
1.062768	2.195168
0.954033	2.006163

A_{T_n}	P_n
0.640246	0.3
1.487275	0.1
2.39008	0.05
3.326314	0.03
6.398667	0.01
8.822253	0.005
11.195786	0.003
18.351506	0.001
19.97441	0.0007

$$L_n \quad H_s \cdot R_E^{\,2} \cdot \sin(\zeta)^2 - 2 \cdot R_E \cdot H_{R_n} \quad H_s \cdot H_{R_n}^{\,2} \quad H_s^{\,2} \cdot \quad H_s - R_E \cdot \sin(\zeta)$$

$$A_{S_n} \quad \frac{L_n}{D_n} \cdot A_{T_n}$$

A_{S_n}	P_n
1.039323	0.3
2.414324	0.1
3.879901	0.05
5.399745	0.03
10.387279	0.01
14.321735	0.005
18.174918	0.003
29.791471	0.001
32.426343	0.0007

Compute A(R,D) for 27 GHz

$$\delta(R) \quad 3.8 \quad 0.6 \cdot \ln \text{Rate}_n$$

$$c_n \quad 0.026 \quad 0.03 \cdot \ln \text{Rate}_n$$

$$B_n \quad 0.83 \quad 0.17 \cdot \ln \text{Rate}_n$$

$$u_n \quad \frac{B_n}{\delta(R)} \cdot c_n$$

$$y_n \quad \alpha_{V27} \cdot u_n$$

$$z_n \quad \alpha_{V27} \cdot c_n$$

$$\gamma(R) \quad \kappa_{V27} \cdot \text{Rate}_n^{\,\alpha_{V27}}$$

$$A_{T_n} \quad \text{if } \delta(R) < D_n, \gamma(R) \cdot \frac{e^{y_n \delta(R)} \quad 1}{y_n} \quad e^{z_n D_n} \quad e^{z_n \delta(R)} \cdot e^{\alpha_{V27} B_n}, \gamma(R) \cdot \frac{e^{y_n \delta(R)} \quad 1}{y_n}$$

$\delta(R)$	D_n
3.506852	3.048803
2.856336	2.987441
2.515255	2.798436
2.28745	2.710554
1.845373	2.591305
1.592703	2.4023
1.416694	2.314417
1.062768	2.195168
0.954033	2.006163

A_{T_n}	P_n
1.451436	0.3
3.160603	0.1
4.904562	0.05
6.666975	0.03
12.254224	0.01
16.463347	0.005
20.51937	0.003
32.448821	0.001
34.916094	0.0007

$$L_n \quad H_s \quad R_E^{\,2}\cdot\sin(\zeta)^2 \quad 2\cdot R_E\cdot H_{R_n} \quad H_s \quad H_{R_n}^{\,2} \quad H_s^{\,2} \quad H_s \cdot R_E \cdot \sin(\zeta)$$

$$A_{S_n} \quad \frac{L_n}{D_n}\cdot A_{T_n}$$

A_{S_n}	P_n
2.35614	0.3
5.130674	0.1
7.961748	0.05
10.822778	0.03
19.892902	0.01
26.726016	0.005
33.310556	0.003
52.676773	0.001
56.682587	0.0007

2.1 Three-parameter lognormal model

```
This program uses NLIN procedure to compute least squares or weighted
least squares estimates of the parameters of a nonlinear model;

options nodate formdlim=',';

* Measured data set

1) independent variable is the rain rate, "rate"

2) dependent variable is the probability ("exceed") of time rain rate
exceeds in yearly percentage,

3) where R is the random variable in exceed = P(rate>R);

data dat1;
input rate exceed;
cards;
120 0.0001
120 0.0012
100 0.0008
100 0.0025
80 0.0020
80 0.0049
60 0.0042
60 0.0080
40 0.0080
40 0.0112
30 0.0116
30 0.0136
20 0.0176
20 0.0195
10 0.0338
10 0.0399
5 0.0782
5 0.1007
2.5 0.1304
2.5 0.2245
1 0.1839
1 0.5053
;



proc nlin;
parms PL=2.33 RL=0.201 SL=1.85;
bounds 0<=PL<=100, 0<=RL<=2, 0<=SL<=3;
temp1=ERFC((LOG(rate)-LOG(RL))/(SQRT(2)*SL));
temp2=(PL/SQRT(3.1415927))*EXP(-((LOG(rate)-LOG(RL))/(SQRT(2)*SL))**2);
model exceed=(PL/2)*temp1;
der.PL=0.5*temp1;
der.RL=((SQRT(2)*SL*RL)**-1)*temp2;
der.SL=((LOG(rate)-LOG(RL))/(SQRT(2)*SL**2))*temp2;
run;
```

2.2 Two-Component Model (Debris)

```
This program uses NLIN procedure to compute least squaers or weighted
least squares estimates of the parameters of a nonlinear model;

options nodate formdlim=',';

*Measured data set

1) independent variable is the rain rate, "rate"

2) dependent variable is the probability ("exceed") of time rain rate
exceeds in yearly percentage,

3) where R is the random variable in exceed=P(rate>R);

data dat1;
input rate exceed;
cards;
40 0.0080
40 0.0112
30 0.0116
30 0.0136
20 0.0176
20 0.0195
10 0.0338
10 0.0399
5 0.0782
5 0.1007
2.5 0.1304
2.5 0.2245
1 0.1839
1 0.5053
;

proc nlin;
parms PL=6.957 RL=0.10 SL=1.81;
bounds 0<PL<20, 0<RL<3, 1<=SL<=2;
temp1=ERFC((LOG(rate)-LOG(RL))/(SQRT(2)*SL));
temp2=(PL/SQRT(3.1415927))*EXP(-((LOG(rate)-LOG(RL))/(SQRT(2)*SL))**2);
model exceed=(PL/2)*temp1;
der.PL=0.5*temp1;
der.RL=((SQRT(2)*SL*RL)**-1)*temp2;
der.SL=((LOG(rate)-LOG(RL))/(SQRT(2)*SL**2))*temp2;
run;


Note:     Stop,     debris     parameters     were     unsatisfactory
```

3 Rain Rate Data

Exceedance (minutes) verses Rain Rate

94 -95

Date	Time		Rain Rate (mm/hr)											Total Rainfall (mm)
	Start	End	120	100	80	60	40	30	20	10	5	2.50	1.00	
941014	12.0	13.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	3.60	7.20	0.40
941015	2.5	5.5	0.00	0.00	0.00	0.50	2.20	7.20	17.10	25.10	31.70	41.20	53.60	12.69
941103	1.0	2.0	0.00	0.00	0.00	0.00	0.00	0.50	2.60	7.10	8.90	13.30	24.20	3.06
941111a	12.0	14.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	2.50	3.60	6.50	0.61
941111b	17.0	20.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00	15.00	0.89
941111c	21.0	24.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00	15.50	40.20	2.09
941112a	0.0	4.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	18.00	36.70	42.90	3.63
941112b	4.0	8.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.20	40.30	2.08
941112c	8.0	12.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.70	20.00	0.78
941112d	12.0	16.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.80	64.70	115.60	6.54
941112e	16.0	20.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	5.80	24.30	60.10	2.94
941112f	20.0	24.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	13.80	0.63
941205a	18.0	22.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	57.00	177.30	6.83
941205b	22.0	24.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	40.30	100.70	4.31
941206a	0.0	4.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	5.90	36.10	142.50	5.80
941206b	4.0	6.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	28.20	1.07
941206c	8.0	12.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	33.30	83.10	172.50	9.73
941227a	4.0	5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.60	21.80	38.90	46.90	4.07
941227b	6.3	7.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
950104	15.0	18.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	21.30	72.70	99.70	6.51
950105a	14.0	16.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	12.60	33.80	1.57
950105b	18.5	22.5	0.00	0.00	0.00	0.00	0.00	0.00	1.00	25.60	59.20	82.00	99.00	12.12
950106	0.0	1.0	0.00	0.00	0.00	0.00	0.00	0.00	2.00	3.40	4.00	5.90	12.20	1.54
950126	9.0	11.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.10	36.40	51.10	61.30	6.51
950213a	14.5	16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.10	8.60	28.80	1.21
950213b	20.0	21.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	4.80	0.22
950214	10.0	11.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.90	1.10	0.15
950215a	4.0	5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.20	4.50	0.16
950215b	15.0	16.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.70	17.30	0.84
950215c	21.0	24.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.30	39.90	70.00	3.76
950216a	0.0	4.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	17.50	36.10	85.70	5.50
950216b	4.0	8.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.60	57.70	2.48
950301	4.0	5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	3.30	0.14
950617	5.0	6.0	0.00	0.00	0.70	1.10	1.50	1.70	2.00	4.80	6.80	10.20	17.10	3.48
950701	2.0	3.0	0.50	2.20	3.90	4.50	5.20	5.90	7.10	7.80	10.20	16.60	27.30	10.07
950720	23.0	24.0	0.00	0.00	0.00	0.00	0.00	1.00	4.30	14.30	22.60	29.40	37.00	5.80
950721	23.0	24.0	5.40	6.00	6.90	8.00	8.40	9.40	10.60	11.40	13.80	16.30	200.58	20.67
950722	0.0	1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.80	16.00	0.75
950817	0.5	2.5	0.60	3.50	11.90	22.60	32.10	34.60	38.90	45.80	56.60	67.30	201.48	46.83
950819	1.5	3.5	0.00	1.60	2.10	4.80	7.70	9.20	10.60	15.60	20.20	28.70	35.20	49.87

950820	22.0	23.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	4.80	0.27
950915a	7.0	11.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	9.80	0.96
950915b	11.0	15.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.10	58.50	2.91
950915c	15.0	19.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.70	24.50	78.68	3.54
950915d	19.0	22.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.90	7.20	23.70	1.26
950915e	22.0	24.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.90	14.30	36.30	1.78
950916	2.0	5.0	0.00	0.00	0.00	0.00	0.00	0.00	1.90	3.90	32.80	72.80	114.70	8.53
950928a	17.0	19.0	0.00	0.00	0.00	0.60	1.60	2.20	4.20	22.30	46.60	64.10	76.20	11.10
950928b	20.0	22.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	5.20	14.10	31.80	1.77

Las Cruces Point Rain Rate Distribution Values (mm\hr)
Verses Percent of Summer 1995 Rain Rate is Exceeded

Rain Rate (mm/hr)	**120.0**	**100.0**	**80**	**60**	**40**	**30**	**20**	**10**	**5**	**2.5**	**1**
Minutes per Year	6.5	13.3	25.5	42.1	58.7	71.7	102.3	209.9	529.1	1179.8	2655.9
Hours per Year	0.1	0.2	0.4	0.7	1.0	1.2	1.7	3.5	8.8	19.7	44.3
Percent of Year	0.0012	0.0025	0.0049	0.0080	0.0112	0.0136	0.0195	0.0399	0.1007	0.2245	0.5053

Exceedance (minutes) verses Rain Rate

95 - 96

Date	**Time**		**Rain Rate (mm/hr)**											**Total Rainfall (mm)**
	Start	End	120	100	80	60	40	30	20	10	5	2.50	1.00	
951106a	15.5	19.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	10.28	0.85
951106b	19.5	21.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.10	0.17
951217	9.5	10.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.50	9.10	0.53
951221	18.0	22.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.30	0.35
960101a	4.0	5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	5.90	0.33
960101b	13.0	17.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.60	1.06
960102	20.5	21.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
960405	17.5	20.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	31.30	1.30
960627	4.5	8.5	0.00	0.50	0.90	1.30	2.50	7.20	12.50	17.70	40.70	117.40	177.10	18.04
960629a	6.8	8.8	0.00	0.00	0.00	0.00	1.50	3.60	4.60	8.30	9.90	10.70	20.60	4.40
960629b	19.5	20.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.90	1.70	0.14
960711	0.5	1.5	0.00	0.00	0.00	0.00	0.00	0.00	1.30	4.00	5.90	7.40	9.70	1.66
960715	12.3	16.3	0.00	2.00	6.20	13.10	14.90	16.00	17.80	31.90	78.70	103.10	119.40	31.22
960725	7.8	8.8	0.00	0.00	0.00	0.00	0.80	1.10	3.10	5.20	10.50	14.10	19.30	3.16
960726	23.0	24.0	0.00	0.00	0.00	0.00	0.00	1.20	2.90	4.40	5.20	6.00	7.70	2.01
960728	21.0	22.0	0.00	0.00	0.50	3.80	9.40	11.70	14.50	16.80	18.50	20.20	24.50	12.74

960731	0.0	2.0	0.00	0.00	0.00	0.00	0.50	1.20	2.40	9.60	18.10	31.20	42.80	5.38
960820	3.0	4.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	3.50	15.50	24.10	1.55
960821	22.0	23.0	0.00	0.00	0.00	0.00	0.70	1.30	2.20	5.70	10.30	15.30	17.90	3.15
960905	21.0	22.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.70	3.20	3.50	8.40	0.71
960911a	10.5	14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.80	26.80	64.50	3.13
960911b	22.8	23.8	0.70	1.80	2.70	3.10	5.10	6.70	12.50	22.60	28.50	35.50	38.60	13.86
960912a	4.5	8.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.40	119.60	189.90	206.20	20.12
960912b	8.5	9.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	4.50	17.70	22.10	1.53
960914	22.5	23.5	0.00	0.00	0.00	0.00	0.80	1.10	5.90	11.90	21.30	29.90	42.00	6.08
960915	2.8	3.8	0.00	0.00	0.00	0.90	5.90	10.00	12.80	17.90	24.50	26.40	30.80	10.91
960926	20.0	21.0	0.00	0.00	0.00	0.00	0.00	0.00	0.10	4.00	6.90	8.80	10.80	1.49

Las Cruces Point Rain Rate Distribution Values (mm\hr)
Verses Percent of Summer 1996 Rain Rate is Exceeded

Rain Rate (mm/hr)	**120.0**	**100.0**	**80**	**60**	**40**	**30**	**20**	**10**	**5**	**2.5**	**1**
Minutes per Year	0.7	4.3	10.3	22.2	42.1	61.1	92.6	178.1	412.2	687.0	968.8
Hours per Year	0.0	0.1	0.2	0.4	0.7	1.0	1.5	3.0	6.9	11.5	16.1
Percent of Year 95-96 Leap Year	0.0001	0.0008	0.0020	0.0042	0.0080	0.0116	0.0176	0.0338	0.0782	0.1304	0.1838
Percent of Year 94-95	0.0012	0.0025	0.0049	0.0080	0.0112	0.0136	0.0195	0.0399	0.1007	0.2245	0.5053
% Mean	0.0007	0.0017	0.0034	0.0061	0.0096	0.0126	0.0185	0.0369	0.0894	0.1773	0.3443

4.1 Mac_rain.xls

```
' RainMac Macro
' Macro recorded 2/23/1996 by Frank J. Paulic Jr.
Sub RainMac()
    FadeFile = GetFile
    If FadeFile = False Then Exit Sub
    Workbooks.OpenText FileName:=FadeFile, _
        Origin:=xlWindows, StartRow:=1, DataType:=xlDelimited, _
        TextQualifier:=xlDoubleQuote, ConsecutiveDelimiter:=False, Tab _
        :=True, Semicolon:=False, Comma:=True, Space:=False, Other _
        :=False, FieldInfo:=Array(1, 1)
    Fade = Application.ActiveWorkbook.Name
    Range("A1:H3602").Select
    Selection.Copy
    Windows("RAIN.XLS").Activate
    Range("A23").Select
    SendKeys String:="{enter}"
    ActiveSheet.Paste
    SendKeys String:="n"
    'Range("V3627").Select
    Range("A1").Select
    Windows(Fade).Activate
    ActiveWorkbook.Close
End Sub
Function GetFile()
    ChDir "C:\ACTS\RAIN\DATA"
    GetFile = Application.GetOpenFilename("Text Files (*.txt), *.txt")
End Function
```

4.2 Mac_rate.xls

```
' RateMac Macro
' Macro recorded 7/11/1996 by Frank J. Paulic Jr.
Sub RateMac()
    FadeFile = GetFile
    If FadeFile = False Then Exit Sub
    Workbooks.OpenText FileName:=FadeFile, _
        Origin:=xlWindows, StartRow:=1, DataType:=xlDelimited, _
        TextQualifier:=xlDoubleQuote, ConsecutiveDelimiter:=False, Tab _
        :=True, Semicolon:=False, Comma:=True, Space:=False, Other _
        :=False, FieldInfo:=Array(1, 1)
    Fade = Application.ActiveWorkbook.Name
    Range("A1:B14402").Select
    Selection.Copy
    Windows("RAINRATE.XLS").Activate
    Range("A23").Select
    SendKeys String:="{enter}"
    ActiveSheet.Paste
    SendKeys String:="n"
    'Range("H14433").Select
    Range("A1").Select
    Windows(Fade).Activate
    ActiveWorkbook.Close
End Sub
Function GetFile()
    ChDir "C:\ACTS\RAINRATE\DATA"
    GetFile = Application.GetOpenFilename("Text Files (*.txt), *.txt")
End Function
```

5 ACTS' Directory and File Paths